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Sediment patterns in relation to vegetative community shifts at Catahoula Lake, Louisiana

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SEDIMENT PATTERNS IN RELATION TO VEGETATIVE COMMUNITY SHIFTS AT CATAHOULA LAKE, LOUISIANA

A Thesis

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by
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Abstract

The processes that control species composition and structure in wetland ecosystems are complex and controlled by many factors including seasonality, depth and duration of flooding, and nutrient dynamics. Catahoula Lake is a floodplain lake that has existed with seasonally fluctuating water levels for at least 4,000 years. The herbaceous vegetation that attracts these waterfowl is slowly being outcompeted by woody vegetation, most notably water-elm (*Planera aquatica*). Our general goal is to understand the processes that cause this shift, focusing on the role of sediments. Our first objective was to use historical aerial imagery to detect historical changes in plant communities at Catahoula Lake, focusing on timing and rates of expansion of woody vegetation. Aerial imagery indicated woody vegetation has been encroaching into the lake bed and the rate of this expansion has increased 249% since major hydrologic alterations in the 1960s. There are three local patterns to this expansion: continuous expansion of woody vegetation, long-term stability of the tree line, and complex patterns of tree establishment. Second, we used ^{137}Cs in lakebed sediments to calculate rates of sedimentation. Results indicated sedimentation was 0.26 cm yr^{-1}, which is increased 225% from the pre-settlement rate of 0.08 cm yr^{-1}. Peaks of ^{137}Cs were muted and deposition rates were similar around the lake, suggesting redistribution of sediments is common. Third, we investigated elemental concentrations in sediment which revealed little spatial variation in recent sediment, but a shift from mixed coastal-plain and Mississippi Alluvial Valley sediments to dominance by acidic, coastal-plain sediments in the past ~60 yr. Sediments are low in organic matter, and carbon and nitrogen concentrations decrease with depth and are being sequestered at low rates (840 t yr^{-1} and 120 t yr^{-1}, respectively). Compared to its condition prior to hydrologic alterations beginning in the 1920s, Catahoula Lake is about 15 cm shallower and the chemical composition of sediments is

more acidic. Although these results are not sufficient to link these differences directly to ecological changes, it is likely the altered sedimentary and hydrologic environment is contributing to the increased dominance of woody vegetation.

Chapter 1. Introduction

The processes that control species composition and structure in wetland ecosystems are complex and include seasonality (Nilsson, Svedmark 2002), depth, and duration of flooding (Casanova, Brock 2000); nutrient dynamics (Bedford et al 1999); and other sediment chemistry. Catahoula Lake near Alexandria, Louisiana has remained a seasonally inundated lake for about 4,000 years (Tedford 2009) and has been experiencing an advancing front of woody, terrestrial vegetation into the lake bed for at least the last 60 years. It has become increasingly important to understand the processes that determine where the tree line ends and the more diverse herbaceous vegetation begins as important waterfowl habitat is lost. Processes controlling this expansion of woody vegetation are largely unknown but sedimentation may be playing a role (Shafroth et al 2002, Reisinger et al 2013). Anthropogenic alterations to watersheds including dam construction, levees, water control structures, and conversion of wetlands to agricultural lands through draining alter hydrology and sediment loads, threatening many of these ecosystems. (Toner, Keddy 1997; Nilsson, Berggren 2014). For example, more than 400,000 ha of Wisconsin wetlands are dominated by reed canarygrass (*Phalaris arundinacea*) due in large part to increased sediment input from erosion of agricultural lands filling in and flattening the heterogeneous topography of tussock sedge meadows (Zedler, Kercher 2004).

Catahoula Lake is a seasonally inundated lake where water levels fluctuate annually about 6 meters and the flooded area of the lake varies by about 90%, resulting in an herbaceous community of moist-soil plants that serves as high energy food for migrating waterfowl. The habitat for shore birds and waterfowl at Catahoula Lake is so important that it has been designated internationally as a wetland of importance under the Ramsar treaty (Gardner, Connolly 2007). However, decreases in herbaceous vegetation in response to expansion of

several woody species into the lake bed have concerned managers for decades (Wills 1965, Bruser 1995, Lotz 1996, Willis 2007, Tedford 2009.)

Catahoula Lake is in the Lower Mississippi Alluvial Valley near the Black River, approximately 30 km northeast of Alexandria, Louisiana. The basin is approximately 20 km long and 5.5 km wide encompassing about 120 km^2 and is the largest freshwater lake in Louisiana (Willis 2009). The lake receives all flow from the Little River and backwater flooding from the Mississippi, Ouachita, Black, and Red rivers, and it drains through a diversion canal to the Black River (Tedford 2009) (Figure 1.1).

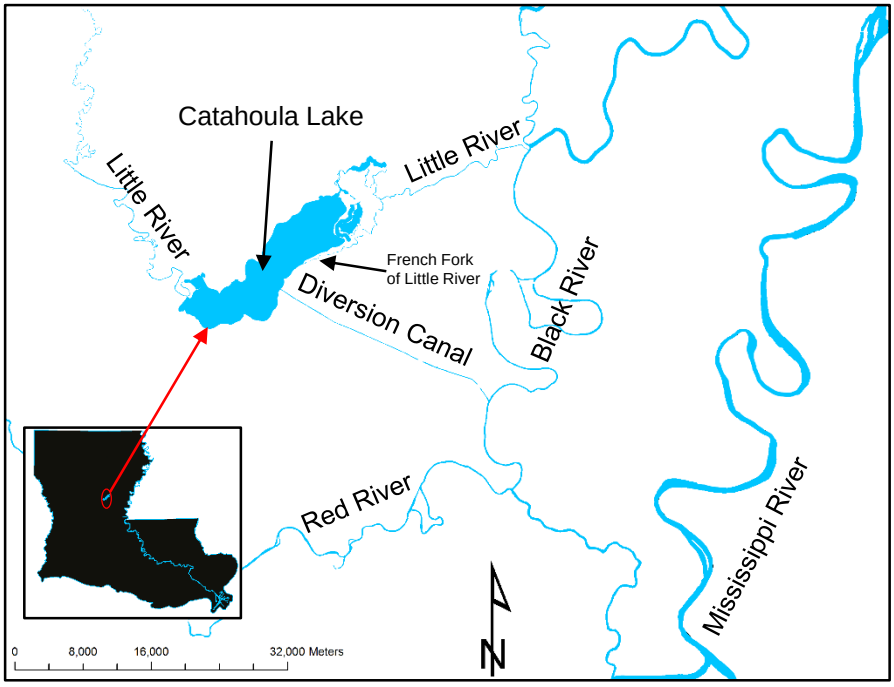

Figure 1.1. Location of Catahoula Lake in relation to the Little, Red, Black and Mississippi rivers and the diversion canal.

Before the canal was built, the lake drained through the French Fork of Little River. A series of locks and dams were built first in 1926 and again in 1972 on the Black River to allow for navigation (U.S. Army Corps of Engineers 1998). These adjustments raised the level of the Black River, and would have retained water in Catahoula Lake to flood it permanently (Sessums

1954). To prevent this and mimic the natural, seasonal drawdown, the Corps of Engineers built the diversion canal to the Black River (U.S. Army Corps of Engineers 1998). Today water is managed through opening and closing a check dam on the Little River near Archie and through opening and closing the water control structure on the diversion canal.

The highly variable water levels at Catahoula Lake have been known for a long time. Dunbar reported in his findings from the expedition of the lower Louisiana Purchase that the lake experienced a dry season from July to November with the exception of the Little River channel (Jefferson 1806). Brown (1943) mentioned lake levels experiencing seasonal variation of more than 7.6 meters (25 feet). Tedford (2009) found that fluctuating water levels have been occurring at least since 4,000 BP. When flooded from November to June, the lake encompasses about 80 km^2 and acts as a limnetic system. In July the lake begins to drain until October, leaving most of the bed dry with a shallow permanent pool of about 8 km^2. Today this fluctuation is managed in a manner that attempts to mimic the natural fluctuations pre-alteration.

Woody vegetation has been expanding into the lake since at least 1952 and the causes are not well understood. Water-elm (*Planera aquatica*) and swamp-privet (*Forestiera acuminata*) are the main woody species expanding into the bed of the lake. They outcompete important waterfowl food sources, most notably chufa (*Cyperus esculentus*), Walter's millet (*Echinochloa walteri*), and sprangletop (*Leptochloa fascicularis*).

Vegetative communities at Catahoula Lake are at least partially controlled by depth, duration of flooding and hydrologic regime (Brown 1943, Wills 1965, Bruser 1995). Brown (1943) and Wills (1965) described the correlation between lake levels and vegetative communities. Bruser's (1995) post-modification study found that decreases in variability of lake levels between August and November may be driving the decrease in herbaceous vegetation.

Amount and composition of lakebed sediments may affect vegetative communities. Sedimentation from outside sources is believed to be low (Wills 1965; Peters, Afton 1993), but previous sediment studies (Meriwether 2007, Tedford 2009) have been inconclusive in regards to recent changes in sedimentation. Increased sediment would lead to a decrease in depth and duration of flooding by changing the topography. Excessive sediment could bury seeds and prevent germination of some plant species (Gleason et al 2003). A change in sediment texture or nutrients could change competitive dynamics among species (Hillel 2004, Havlin et al 2005).

Our overall objective is to better understand the processes that cause vegetation shifts at this complicated, floodplain lake. We have three specific objectives to accomplish this. First, we use historical aerial imagery to quantify historical changes in plant communities at Catahoula Lake, focusing on timing and rates of expansion of woody vegetation. Second, we use ^{137}Cs concentration in sediments to determine rate of recent sedimentation. Third, we investigate sediment composition with emphasis on particle size and elemental concentration to determine whether sediment sources and depositional patterns may have changed recently.

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Chapter 2. Rates, and Patterns of Woody Expansion at Catahoula Lake, Louisiana

Introduction

Catahoula Lake, near Alexandria, Louisiana, is a backswamp lake in the Lower Mississippi Alluvial Valley that is experiencing a shift in vegetation. It is seasonally inundated and palustrine over much of its basin but with a permanent pool in the center. Lake levels fluctuate about 6 m each year, going almost completely dry beginning in July to about November (USGS 2002). This annual variation promotes growth of wetland plants like sprangletop (*Leptochloa fascicularis*), Walter's millet (*Echinochloa walteri*) and chufa (*Cyperus esculentus*), which are sources of carbohydrates for wintering waterfowl and migratory birds using the lake as a stop along their route (Reinecke et al. 1989; Woolington, Emfinger 1989; Peters, Afton 1993). For several decades the lake has been experiencing a shift from these herbaceous plants toward woody vegetation, especially water-elm (*Planera aquatica*) and swamp-privet (*Forestiera acuminata*).

The variability of Catahoula Lake water levels has been long known. Tedford (2009) found that lake water levels have been fluctuating at least since 4,000 BP. Dunbar reported in his findings from the expedition of the lower Louisiana Purchase that the lake experienced a dry season from July to November with the exception of the Little River channel (Jefferson 1806). Brown (1943) mentioned lake levels experiencing seasonal variation of more than 25 feet (7.6 meters). When flooded from November to June, the lake encompasses about 80 km^2 and acts as a limnetic system (See B in Figure 2.1). In July the lake begins to drain until October, leaving most of the bed dry with a shallow permanent pool (See A in Figure 2.1) of about 8 km^2.

Hydrologic alterations to Catahoula Lake and the surrounding rivers have been occurring since at least the early 1920s. Catahoula Lake receives inputs from the Little River and

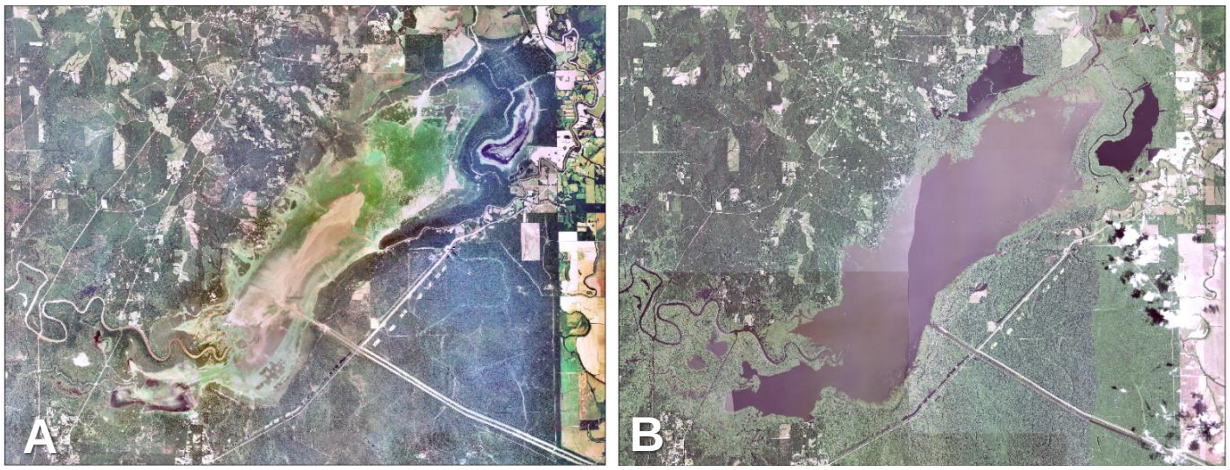

Figure 2.1. Catahoula Lake in these mosaics of georectified digital quarter quadrangle aerial imagery taken by the USDA National Agriculture Imagery Program (NAIP) at 1:40,000 resolution. A.) August-September 2007, low water. B.) July 2009, high water.

backwater flooding from the Mississippi, Ouachita, Black, and Red rivers. Prior to alterations, the lake drained through the French Fork of Little River but presently drains through a diversion canal that runs from near French Fork to the Black River (Figure 1.1). A series of locks and dams was built first in 1926 and again in 1972 on the Black River to allow for navigation (U.S. Army Corps of Engineers 1998). These structures raised the minimum level of the Black River and would have flooded Catahoula Lake permanently so the sole drainage through French Fork of the Little River was no longer adequate (Sessums 1954). To allow the natural, seasonal drawdown, the Corps of Engineers built the diversion canal (Bruser 1995, Willis 2009). Today water is managed by opening and closing the water control structure on the diversion canal and by a weir on the French Fork near Archie, Louisiana.

It remains generally poorly understood why Catahoua Lake is an open body of water and not a forested wetland. Tedford (2009) has shown that ecologic conditions (caused by fluctuating water levels) have been similar for the past 4,000 years. Some theories suggests that human disturbance is at least partially responsible for maintaining this unforested condition. For example, grazing by cattle and feral hogs has been sometimes cited as one reason Catahoula

Lake has remained unforested (Bruser 1995, Willis 2009). However, Lotz (2000) found no evidence that grazing affected the establishment of woody species. Thus, the recent expansion of woody vegetation indicates there has likely been a recent change in some main natural process causing the ecosystem to cross a threshold toward forest occupation.

Expansion has been occurring since at least 1952. However, Wills (1965) reported the rate as "very slow". The shift from herbaceous vegetation toward woody plants at Catahoula Lake is not desired because woody vegetation is inferior habitat for most waterfowl (Fredrickson 1982, Weller 1989). By 1977 10,000 acres of peak waterfowl food area was not being used due to encroachment of water-elm and swamp-privet (Wills, Davis 1977).

The timing, exact extent, and causes of woody expansion into the lake bed are poorly understood but several studies have been done. Vegetative communities at Catahoula Lake are at least partially controlled by depth and duration of flooding (Brown 1943, Wills 1965, Bruser 1995). Brown (1943) found a correlation between lake levels and vegetative communities and defined seven distinct vegetation zones presumably controlled by depth and duration of flooding. Wills (1965) concentrated mainly on the herbaceous ground cover on the lake bed and similarly concluded that plant zonation on the lake was correlated to depth and duration of flooding in response to the topography of the lake bed. Bruser's (1995) post-modification study suggested that decreases in variability of lake levels between August and November may be driving the decrease in herbaceous vegetation.

Information about historic vegetation management of the lake is incomplete, but written records indicate management of the lake to combat expansion of woody vegetation has been occurring since at least 1952. Wills (1965) noted that after the Louisiana Wildlife and Fisheries commission removed about 12 km^2 of water-elm and swamp-privet during 1954-1957, the

species was very slow to re-invade. This launched an aggressive campaign to remove the woody vegetation that continued through the late 1970s. Joshi (2012) discovered about 73% of the water-elm sampled were established after the canal was built in 1972. However the oldest trees were 131 years old, pre-dating any hydrologic changes to the lake. Today managers use mowing, burning, and herbicide to eliminate young water-elm and swamp-privet on the bed of the lake. These techniques are both costly and inefficient.

Improved understanding of the timing and extent of historic expansion of woody vegetation is needed to better understand the reasons for expansion and to design appropriate management. The objective of this research is to quantify the amount, rate, and location of woody expansion into the lake and better understand patterns of expansion. To do this, we used aerial imagery in combination with tree ages obtained from tree rings by Joshi (2012).

Methods

We examined U.S.D.A. aerial imagery from 1940 (See A in Figure 2.2), 1966 (See B in Figure 2.2) and 2007 (See A in Figure 2.1) and Wills' (1965) map of plant types (See C in Figure 2.2) to quantify the extent and amount of expansion of woody vegetation. Imagery was selected by considering time of year, age, resolution, and water level. We scanned the 1940 and 1966 imagery and imported it into ARCMap 9.3.1 where it was georeferenced to the 2007 USDA imagery from the National Agriculture Imagery Program (NAIP). The imagery was then rectified to the Universal Transverse Mercator (UTM) coordinate system and mosaicked using ERDAS Imagine 2010. To establish our area of interest, we also scanned and georeferenced Wills' (1965) vegetation map and delineated the outer boundary as the outer extent of the water-elm and swamp-privet zone. We analyzed the aerial imagery from 1940, 1966 and 2007 using air photo interpretation and ARCMap. We used the density classifications by Paine (1981) to delineate

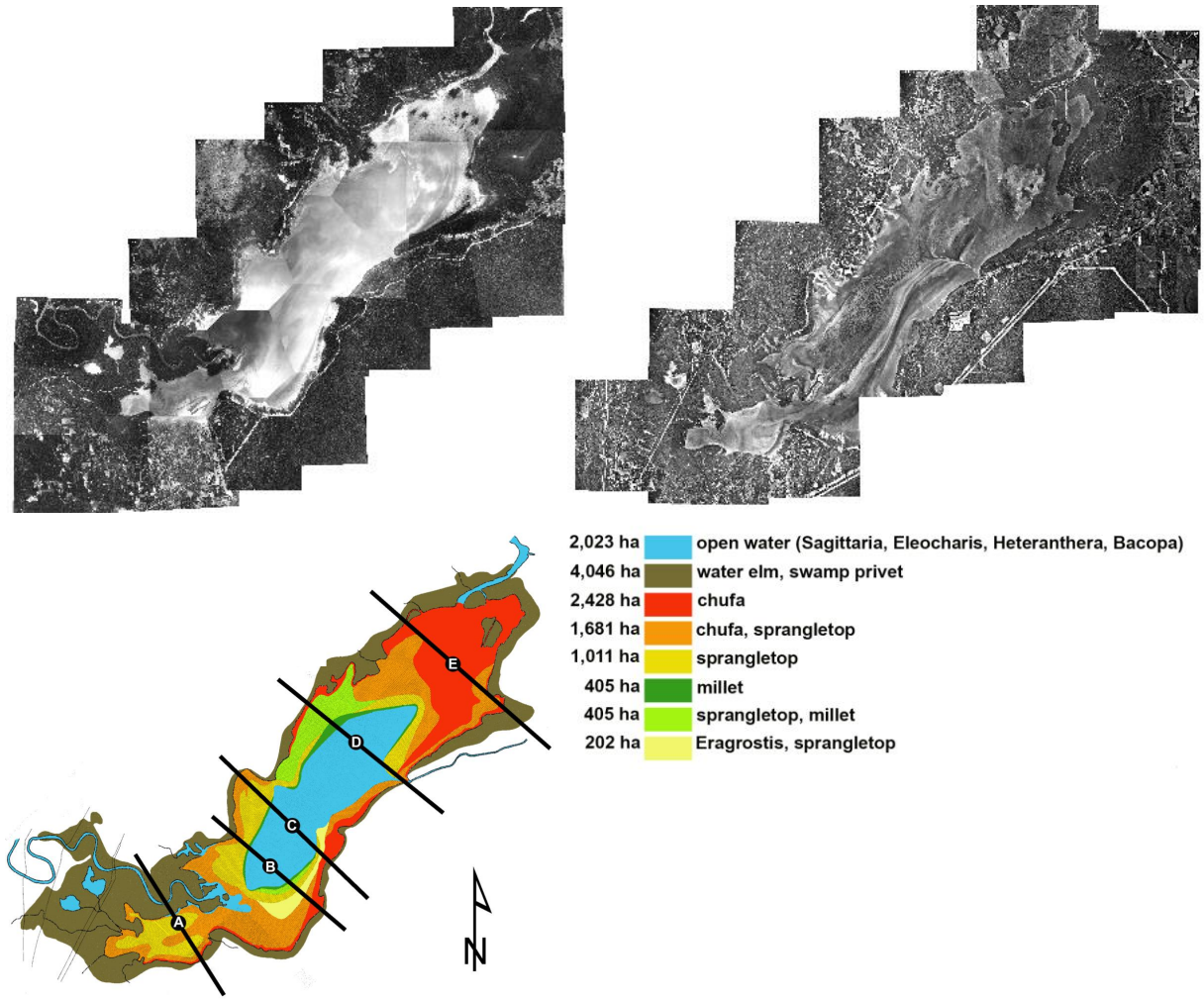

Figure 2.2. Mosaics of georectified digital quarter quadrangle aerial imagery captured by the USDA Farm Service Agency at 1:20,000 resolution in September, 1940 (A) and November 1966 (B). and Wills (1965) map of, Catahoula Lake Plant Types map (C) with Wills' original transects marked as A-E.

polygons of existing woody vegetation from 20-100% cover in classes of sparse-moderate (11-50%) or moderate-dense (50-100%). Overlap in the resulting polygons was evaluated as expansion or removal of woody vegetation between years. We overlaid water-elm tree ring data from Joshi (2012) on the imagery and polygons to compare the two and determine patterns of expansion or recession.

Results

Aerial imagery indicated woody vegetation is expanding into the lakebed and the rate of expansion has increased since 1966. Between 1940 and 1966 about 1.6 km^2 of woody expansion occurred, which is 0.17% of formerly-herbaceous lakebed per year. Between 1966 and 2007 the coverage by woody plants increased 8.8 km^2, or 0.58% per year. Between 1940 and 2007 the lake experienced expansion of 10.4 km^2, or 29.3% overall.

In 1940 there was a total of 35.5 km^2 of woody vegetation in the water-elm zone, which was 29.1% of the lake bed (Figure 2.3). The 1966 imagery showed 33.0 km^2 of pre-existing woody vegetation indicating removal of 2.4 km^2. In addition 4.l km^2 of new woody vegetation expanded into the lake between 1940 and 1966.

In 1966 there was a total of 37.1 km^2 of woody vegetation in the water-elm zone, which was 30.4% of the lake bed (Figure 2.3). The 2007 imagery showed 34.6 km^2 of pre-existing woody vegetation indicating removal of 2.6 km^2. In addition 11.3 km^2 of new woody vegetation expanded into the lake between 1966 and 2007. In 2007 there was a total of 45.9 km^2 of woody vegetation in the water-elm zone, which was 37.6% of the lake bed.

Some historic practices to remove woody vegetation are evident in aerial images of the water-elm zone. Removals have been concentrated in three places: the northeast end of the lake, south of the diversion canal and the delta of Little River. A large portion of the isolated group of trees that existed in the northeast portion of the lake in 1966 has been removed, contributing the most to the 2.6 km^2 of removed woody vegetation. In the southwestern part of the lake, north of the entrance of the Little River, are scars consistent with extensive removal of vegetation by heavy equipment (See A in Figure 2.4). These practices likely occurred in the 1950s-1970s and are reflected in the 1966 imagery. Subsequent to removal, this location is not becoming

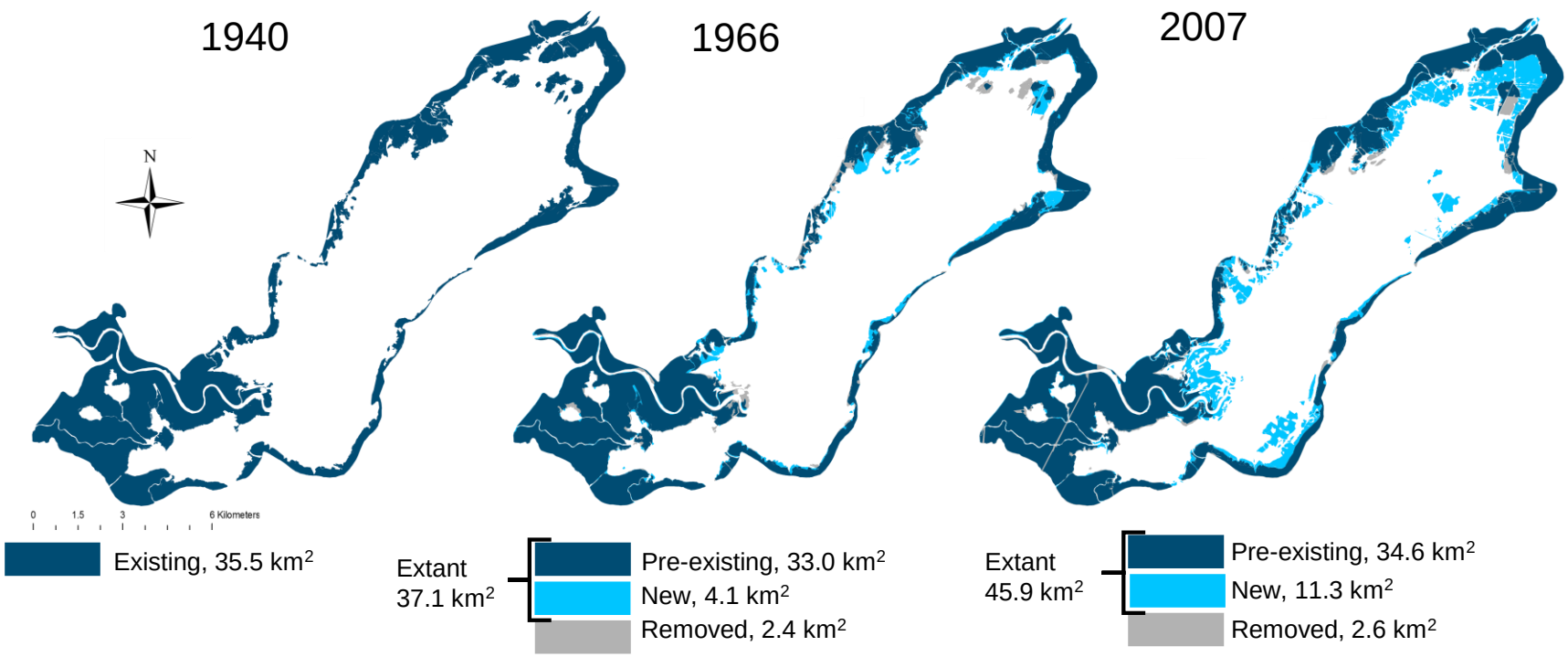

Figure 2.3. Expansion of woody vegetation at Cathoula Lake from 1940 to 2007.

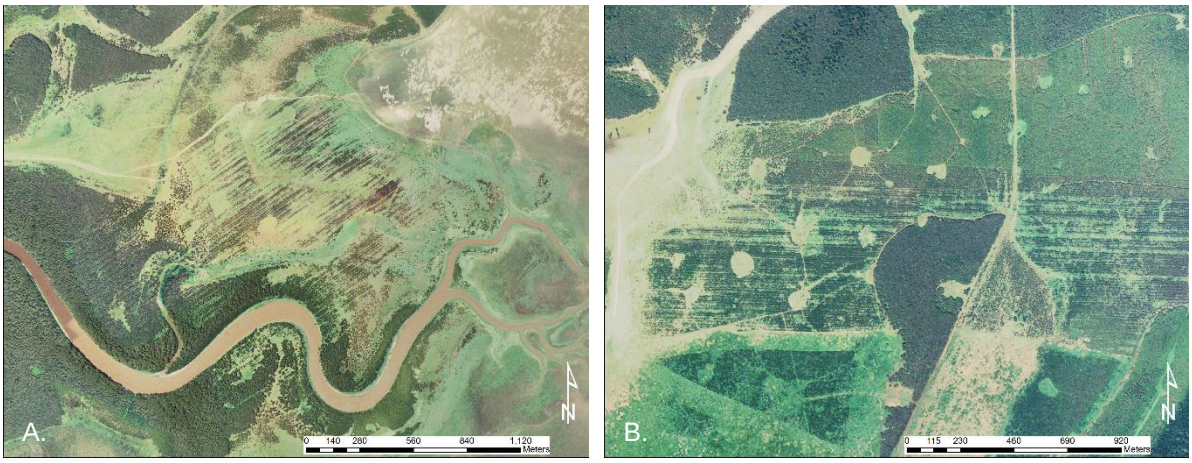

Figure 2.4. Historic practices evident in aerial imagery are A.) scars consistent with extensive removal of vegetation by heavy equipment and B.) clearings created around hunting blinds by waterfowl hunters (USDA aerial imagery from 2007)

re-colonized. In many places around the lake, management by waterfowl hunters is evident in small clearings that surround hunting blinds (See B in Figure 2.4).

Using Joshi's (2012) tree ring data to confirm the aerial imagery and woody expansion delineations, we observed three patterns of expansion. In the first pattern, younger trees are at the encroaching margin and older trees behind (Figure 2.5). This pattern was evident at 43% of sites. This indicates a pattern of continuous encroachment. The second pattern is one of long-term stability (Figure 2.6). This represented 21% of sites. Here we found old and young trees mixed to the edge. The final scenario, accounting for 36% of sites, complex (Figure 2.7). In some cases, younger trees are filling in behind an advanced front, and in others there was no discernible pattern of ages.

There was no obvious spatial distribution of the three patterns of encroachment (Figure 2.8). Continuous encroachment occurred in the southernmost portion of the lake, near the entrance to the canal and directly across from the canal, and just north of the canal entrance. Long term stability occurred mostly in the northeastern corner of the lake. Complex patterns of encroachment occurred just south of the entrance to the canal, just north of the delta formed by

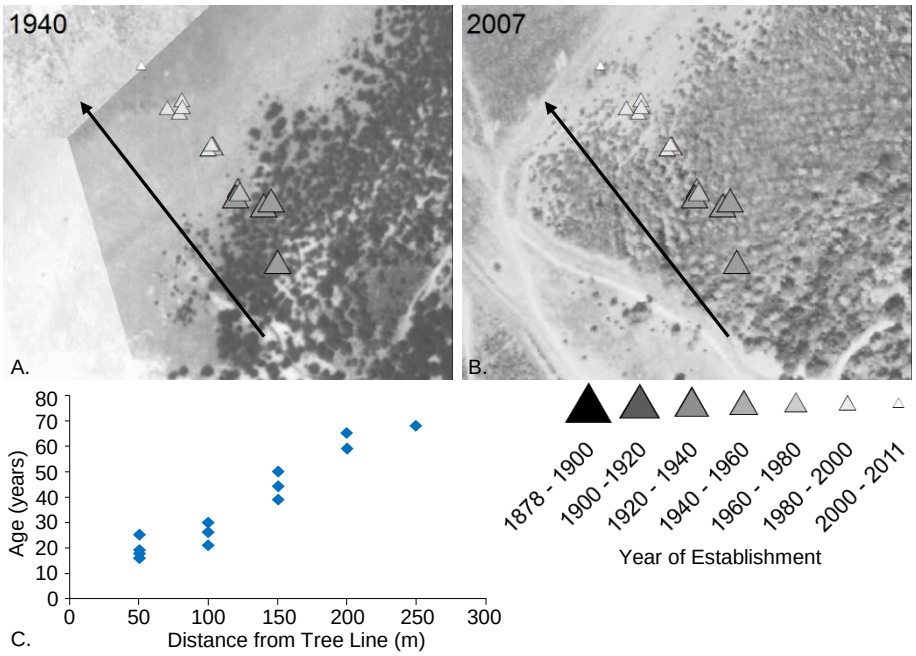

Figure 2.5. Example of continuous encroachment pattern of woody vegetation. Triangles show locations of sampled trees and dates of tree establishment as estimated by Joshi (2012). Red arrows point toward lake center. (A. USDA aerial imagery from 1940; B. USDA aerial imagery from 2007; C. Age of trees in relation to distance from 2012 tree line)

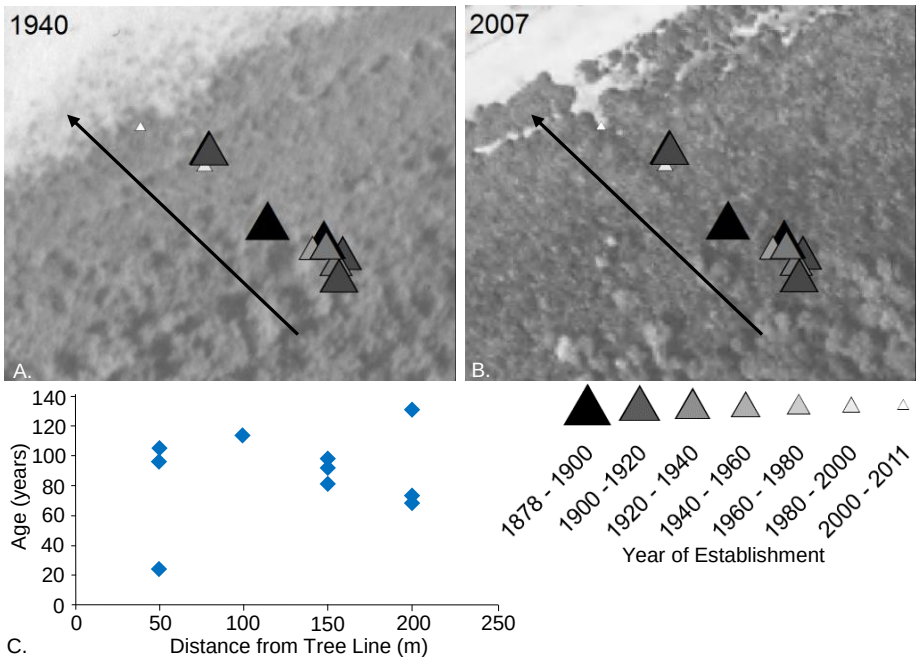

Figure 2.6. Example of long-term stability pattern of woody vegetation extent. Triangles show locations of sampled trees and dates of tree establishment as estimated by Joshi (2012). Red arrows point toward lake center. (A. USDA aerial imagery from 1940; B. USDA aerial imagery from 2007; C. Age of trees in relation to distance from 2012 tree line)

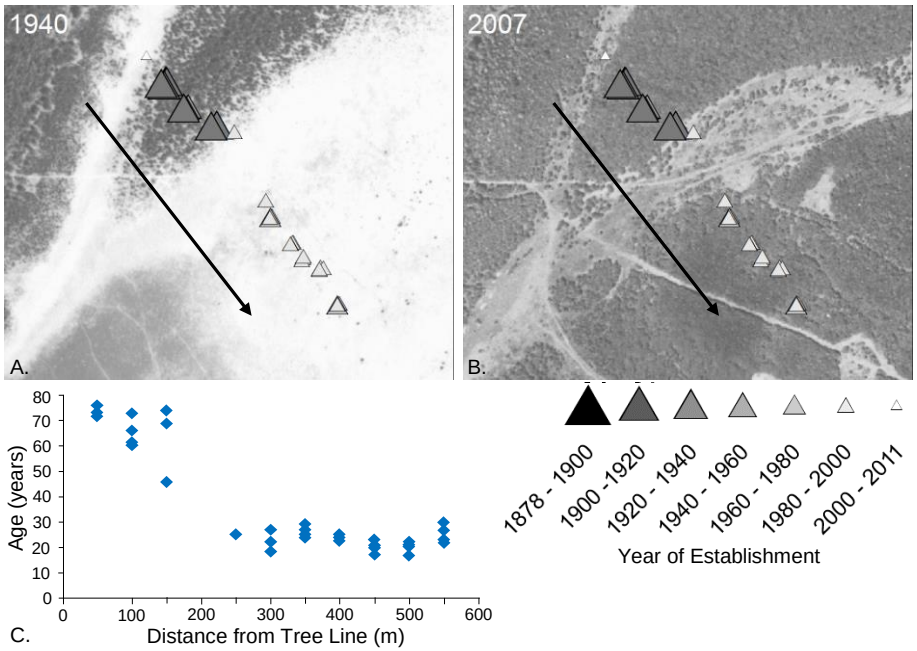

Figure 2.7. Example of complex pattern of encroachment pattern of woody vegetation. Triangles show locations of sampled trees and dates of tree establishment as estimated by Joshi (2012). Red arrows point toward lake center. (A. USDA aerial imagery from 1940; B. USDA aerial imagery from 2007; C. Age of trees in relation to distance from 2012 tree line)

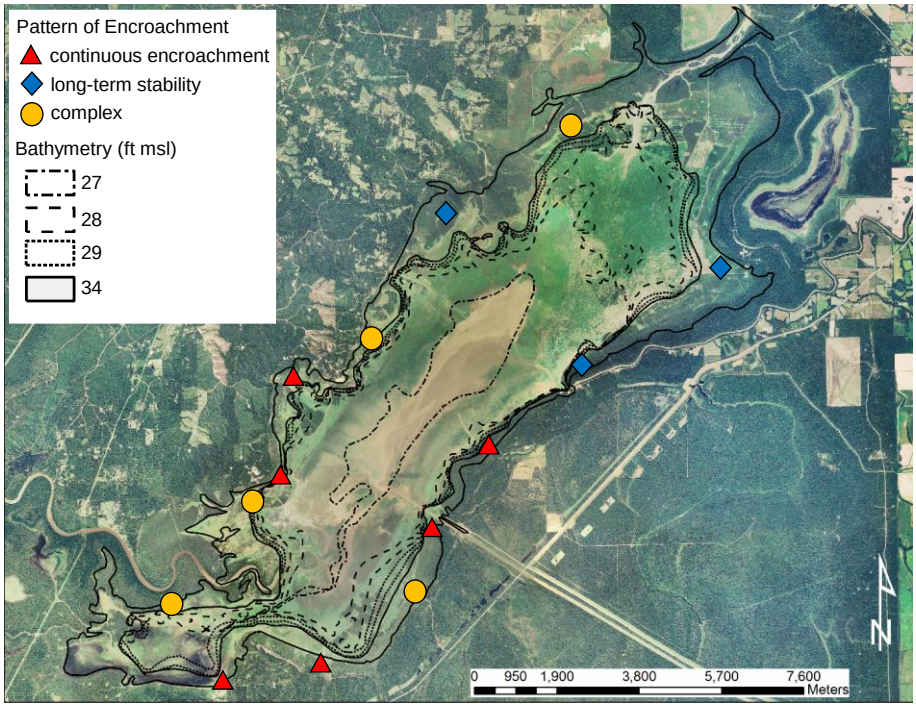

Figure 2.8. Spatial distribution of three patterns of woody encroachment (USDA aerial imagery 2007).

encroachment occurred just south of the entrance to the canal, just north of the delta formed by the entrance of Little River, and at the northern end of the lake on the north side of the lake.

Discussion

The paucity of quality aerial imagery obtained at low water conditions affected estimates of the extent of tree cover. Because most of the aerial imagery available was collected by the USDA during the early growing season, it was difficult to find imagery of the lake bed at low water (in the fall). The aerial imagery from 1940 was the earliest, highest quality, complete imagery we found prior to construction of the canal. However, water levels were higher than ideal for delineation.

The high water in the 1940 imagery means that small trees are not visible beneath the water. Therefore estimates of the extent of woody vegetation from this imagery are low. The effect of this bias is to decrease the estimated rate of woody vegetation expansion in the 1940-1966 period, which would be consistent with Wills (1965) statement that the rate of expansion was "low." Thus, while we estimated the rate of expansion from 1966-2007 was ~2.5 times that of the 1940-1966 period, it is likely the real rate of increase was higher. Our estimates of the rate of expansion of woody plants into the bed of Catahoula Lake are lower than the simple rate of colonization because of extensive and aggressive control efforts. In addition to institutional programs, informal clearings are evidence of widespread efforts by hunters to modify vegetation conditions.

Bruser (1995) concluded that water-elm expansion increased as a result changed variation of fall water levels after the construction of the diversion canal. Our results between 1940 and 1966 demonstrate that expansion of woody vegetation was occurring before the canal was added.

The three patterns of encroachment we discerned could be indicative of processes occurring at the lake. Gradual, constant encroachment could be evidence of change like sediment deposition. Ongoing sediment deposition could be causing steadily decreasing depth and duration of flooding. Long-term stability suggests the opposite: no change is ocurring. Stability may also signify that changes are occurring that prohibit tree seedling establishment, but not survival of existing tress. Water-elm seedlings are not as tolerant of changes to depth or duration of flooding in the growing season or canopy density as established trees (Rayner 1976). Expansion that is more chaotic may be caused by widespread, lake-wide changes toward conditions that favor establishment, but with stochastic and episodic failure and success of cohorts that interact with minor disturbances. One of these minor disturbances may be wave action, which could be disturbing seedlings and preventing establishment. Another may be localized inputs of chemically different sediments.

Spatial distribution of the three patterns of encroachment indicate more stability at the north end of the lake than the south end (Figure 2.8) but management efforts may be masking the actual encroachment. A pattern of stability suggests no change is ocurring to drive encroachment or changes are ocurring that prohibit seedling establishment, however there is a long history of removal of water-elm and swamp-privet in this area. This is evidenced by scarring in the USDA aerial imagery from 1966 and known management attempts by the Louisiana Department of Wildlife and Fisheries (personal communication, Steve Smith, Larry Reynolds, LDWF, 2012).

The majority of continuous encroachment patterns are located near the diversion canal and the input of Little River. These areas may be experiencing a seasonally constant rate of sedimentation that is determined by the seasonal drawdown and flooding of the lakebed.

There are areas of complex patterns of encroachment scattered around the lake indicating that localized disturbances are affecting expansion across the lakebed with no obvious patterns. Several of these occur near the input of Little River where the flow may drive scour, which affects seedling recruitment and establishment in turn. Another complex pattern occurs to the north of the lake where the inputs of several small creeks may be responsible for similar processes.

Elevation may also be affecting the patterns we found at each site because the sites we analyzed were based on Joshi's (2012) tree age data, which was most often collected at the 34 foot contour. However, the available bathymetric data does not have fine resolution and there is a large gap in it between 29 and 34 feet.

Woody encroachment has occurred at other wetlands where anthropogenic changes have altered hydrology. Reelfoot Lake in Tennessee has experienced expansion of woody species and less coverage of giant cutgrass (*Zizaniopsis miliacea*) due to stabilized water levels (Winstead, King 2006). In urban and suburban wetlands in several watersheds of northwestern Indiana, encroachment of the woody species *Salix spp*. and *Populus deltoides* occurs in drained wetlands or those with significant litter accumulation, which are both symptoms of altered hydrology (Choi, Bury 2003).

Conclusions

Woody vegetation has been encroaching into the lake bed of Catahoula Lake and outcompeting herbaceous vegetation. Although encroachment has been occurring for at least 80 years, the rate of expansion is faster in recent decades than it was more than 50 years ago. Why exactly expansion is occurring is largely unknown but there are three patterns. Continuous expansion, which suggests an ongoing process, is occurring near the major inputs and outputs of

the lake. Long term stability of water-elm and swamp-privet are more common in the north end of the lake, but management attempts may be masking the real patterns of expansion there. The rest of the lake is experiencing complex patterns of expansion that are possibly being affected by minor, localized disturbances.

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Chapter 3. Sediment Deposition Amounts and Rates at Catahoula Lake, Louisiana

Introduction

Sedimentation is an important process responsible for wetland ecosystems. For example, sediment can carry with it nutrients for plant growth, increasing productivity of the wetland (Kummu et al 2008). Sediment burial of seeds can reduce seedling emergence (Gleason et al 2003). As sediment settles it may cover photosynthetic substrates and seed banks that may alter plant communities by impeding photosynthesis and the re-colonization process of plants. (Rybicki, Carter 1986, Hartleb et al. 1993, Jurik et al. 1994, Wang et al. 1994). Sedimentation can reduce the number of species and the total number of individuals recruited from the seed bank (Jurik et al. 1994). Increased sediment decreases depth and duration of flooding through changing the topography of the lake bed. These changes in topography therefore indirectly affect the length of the growing period.

The processes that control species composition and structure in wetland ecosystems are complex and include seasonality (Nilsson, Svedmark 2002), depth, and duration of flooding (Casanova, Brock 2000); nutrient dynamics (Bedford et al 1999); and other sediment chemistry. Catahoula Lake near Alexandria, Louisiana has remained a seasonally inundated lake for about 4,000 years (Tedford 2009) and has been experiencing an advancing front of woody, terrestrial vegetation into the lake bed for at least the last 60 years. It has become increasingly important to understand the processes that determine where the tree line ends and the more diverse herbaceous vegetation begins as important waterfowl habitat is lost. Processes controlling this expansion of woody vegetation are largely unknown but sedimentation may be playing a role (Shafroth et al 2002, Reisinger et al 2013). Anthropogenic alterations to watersheds including dam construction, levees, water control structures, and conversion of wetlands to agricultural

lands through draining alter hydrology and sediment loads, threatening many of these ecosystems. (Toner, Keddy 1997; Nilsson, Berggren 2014). For example, more than 400,000 ha of Wisconsin wetlands are dominated by reed canarygrass (*Phalaris arundinacea*) due in large part to increased sediment input from erosion of agricultural lands filling in and flattening the heterogeneous topography of tussock sedge meadows (Zedler, Kercher 2004).

Current and historic sedimentation and erosion patterns are largely unknown at Catahoula Lake but several studies have reported on the state of sediments at the lake. Russell (1942) as reported by Willis (2009), Brown (1943), Bruser (1995), and Willis (2009), refer to sedimentation as being negligible throughout most of the lakebed. Russell (1942), as reported by Willis (2009), found sedimentation occurring in areas where tributaries have produced natural levees and deltas as has occurred at Devil's Creek and Hemphill Creek that enter the lake from the north. Brown (1943) photographed baldcypress trees at French Fork with exposed roots indicative of erosion of sediment that must have been higher at the time of establishment. Tedford (2009) used ^{210}Pb and ^{14}C dating to estimate sedimentation rates at Catahoula Lake increasing from ~0.02 – 0.03 cm yr^{-1} about 4000 ybp to ~0.14-0.48 cm yr^{-1} about 1800 AD-2004 and attributed this increase in sedimentation to anthropogenic impacts for the past 200 years.

There have been two previous efforts to quantify deposition rates at Catahoula Lake, but neither is sufficient to determine whether deposition is related to recent changes in ecology. Meriwether (2007) and Tedford (2009) both used radioisotopes to calculate sedimentation rates. However, both studies collected profiles from near the center of the lake, which is not the location of the woody expansion zone. They both used ^{137}Cs, which is a fallout product deposited over North America during nuclear testing in the 1950s and 1960s and is a useful tracer for dating sediments in lakes and wetlands (DeLaune et al 1978; Ritchie, McHenry 1990; Callaway

et al 1996). Sediment accretion is determined by locating the depths in the sediment horizon where the first significant ^{137}Cs deposition, or peak ^{137}Cs fallout occurred in 1954 or 1963, respectively (Pennington 1973; Ritchie, McHenry 1990).

Our general objective is to determine whether sedimentation is an important process controlling ecologic processes in the lake. Here, the specific objectives are to use ^{137}Cs to calculate the amount of sediment deposited and the rate at which it has occurred in recent decades during the period of most rapid ecologic change, and to examine the spatial variability of recent deposition around the lake for evidence of controlling processes.

Methods

^{137}Cesium Analysis

We collected 14 sediment profiles to test for the presence of ^{137}Cesium. Profiles were sampled in the zone of expansion of water-elm, near, elevation 10.4 m (34 ft.) to a depth of 0.5 m. These depths of sampling correspond to approximately 167 years of deposition according to sedimentation rates estimated by Tedford (2009). Profiles were collected by hammering 10 cm diameter aluminum tubes to a depth of about 50 cm and digging them out to retrieve them. A wooden cap was placed on top of the tube to lessen the impact of the blow and prevent compaction (See A in Figure 3.1). After collection, rubber caps were placed on the ends of the tubes to maintain the integrity of the samples during transport. Any extra space in tubes was filled with plastic bags to prevent movement of the sample in the tube. For the few samples that still became slightly compacted or disaggregated inside the pipe, we corrected later analysis by indexing to marks made on the pipe during collection to indicate the ground surface.

In the laboratory, tubes were cut in half lengthwise with a jigsaw to remove the sample (See B in Figure 3.1). Profiles were divided into 3 cm increments, oven-dried to 105° C,

weighed, and ground with a Humboldt soil grinder and disaggregated to pass an ASTM number 10 sieve.

Figure 3.1. A.) Drew Fowler drives an aluminum tube into the ground at the site of profile D5. B.) profile D1 in its tube after being cut open lengthwise.

Samples were analyzed for ^{137}Cs by with a lithium-drifted germanium detector and multichannel analyzer (DeLaune et al. 1978). We calculated sediment amount by locating the deepest horizon in which we detected significant ^{137}Cs, but interpreting low ^{137}Cs layers at the base of samples as a zone of disturbance where we assumed ^{137}Cs was trans-located downward or the result of sediment mixing. The basal elevation of significant ^{137}Cs was then assumed to have been deposited in 1954, which corresponds to the first year radioactive fallout became detectable in the sediment after its initial introduction to the atmosphere in 1952 (Pennington et al. 1973; Ritchie, McHenry 1990). In samples with clearly visible peaks in ^{137}Cs concentration with depth, we associated the peak with 1963 (DeLaune et al. 1978), and we interpreted samples

without clear peaks as being subject to sediment mixing subsequent to deposition (Brenner and Kenney 2013).

Particle Size Analysis

We collected 38 total sediment profiles for particle size analysis: the 13 collected to 0.5 m for ^{137}Cs analysis, 12 profiles to a depth of 1 m collected with a Giddings Probe and later divided into 5 cm increments, and 12 profiles collected by digging pits and cutting 5 cm portions out of the profile. All samples were then oven-dried to 105° C, ground with a Humboldt soil grinder and disaggregated to pass an ASTM number 10 sieve.

All samples were analyzed for particle size on a 25 g subsample using the pipette method (Gee, Bauder 1986). We analyzed the top 15 cm of each profile for organic matter using the loss on ignition method which removes organic matter in a subsample by combusting it in a muffle furnace at 400°C for 16 hours. (Nelson, Sommers 1996). Organic matter in excess of 5% can cause aggregation of clay particles that cannot be disaggregated easily during particle size analysis (Gee, Bauder 1986), so to prevent that those samples were treated with H_2O_2 and heated until effervescence no longer occurred. We added 20 ml 50 g/L sodium hexametaphosphate $(NaPO_3)_6$ to the samples and 150 ml of water and placed them in a shaker overnight. Sand particles were collected by washing the sample in a 53 µm sieve. The sand was then dried in an oven at 105°C and weighed. The remaining sample was agitated in a 1000 ml graduated cylinder and left to settle for approximately 8 hours. Next, a subsample of 25 ml was taken by pipette, dried and weighed, and this subsample used to estimate the clay fraction.

Results

Presence of ^{137}Cs indicated 10.0-18.0 (14.8 ± 0.16) cm of sediment deposited at Catahoula Lake between 1954 and 2012 (Table 3.1). These overall rates correspond to annual

rates of sedimentation 0.17- 0.31 (0.26 ± 0.13) cm/year (Figure 3.2). Over an area of 80.94 km^2 and at mean bulk density 0.99 kg m^{-3} mass of this net sediment deposition over 58 years is 1.18 $x10^6$ t, or 204,350 t yr^{-1}. In general, 1963 peaks were not visible (Figure 3.3), so estimates of sediment deposition at finer timescales are not available and it appears that sediment mixing was widespread. We could not locate the 1954 horizon in profiles D10, D11 and D13 possibly because of high sand content (Ritchie, McHenry 1990; Saengkul et al 2013).

Table 3.1. Sedimentation estimates based on ^{137}Cs analysis of sediment profiles. Locations of profiles are depicted in Fig. 3.2.

Core	Depth to 1954 horizon (cm)	Estimated sedimentation rate		Est. sediment load (t yr^{-1})
		(cm yr^{-1})	(t ha^{-1} yr^{-1})	
D1	10.0	0.2	18.0	146,000
D2	16.8	0.3	26.6	215,000
D3	13.0	0.2	22.1	179,000
D4	16.0	0.3	23.1	187,000
D5	15.0	0.3	27.0	219,000
D6	15.0	0.3	22.1	179,000
D7	15.0	0.3	25.5	207,000
D8	18.0	0.3	35.2	285,000
D9	12.0	0.2	21.2	172,000
D12	17.5	0.3	31.7	257,000
mean	14.8	0.3	25.2	204,600

Particle size analysis indicated homogenous particle size with depth for the majority of profiles (32 of 35 profiles) with a few exceptions. Most (27 of 35) of sediments were clays or silty clays (NRCS 1993) (Figure 3.4, Table 3.2). Two of the 35 profiles were dominated by clay but contained sand lenses 20-40 cm thick. Five of the 35 profiles were sandy throughout. Discontinuities in particle size with depth occurred in 6 profiles, changing from fine to more coarse sediments with depth in profiles D and E and from coarse to fine sediments with depth in profiles M, N, D10, and D11.

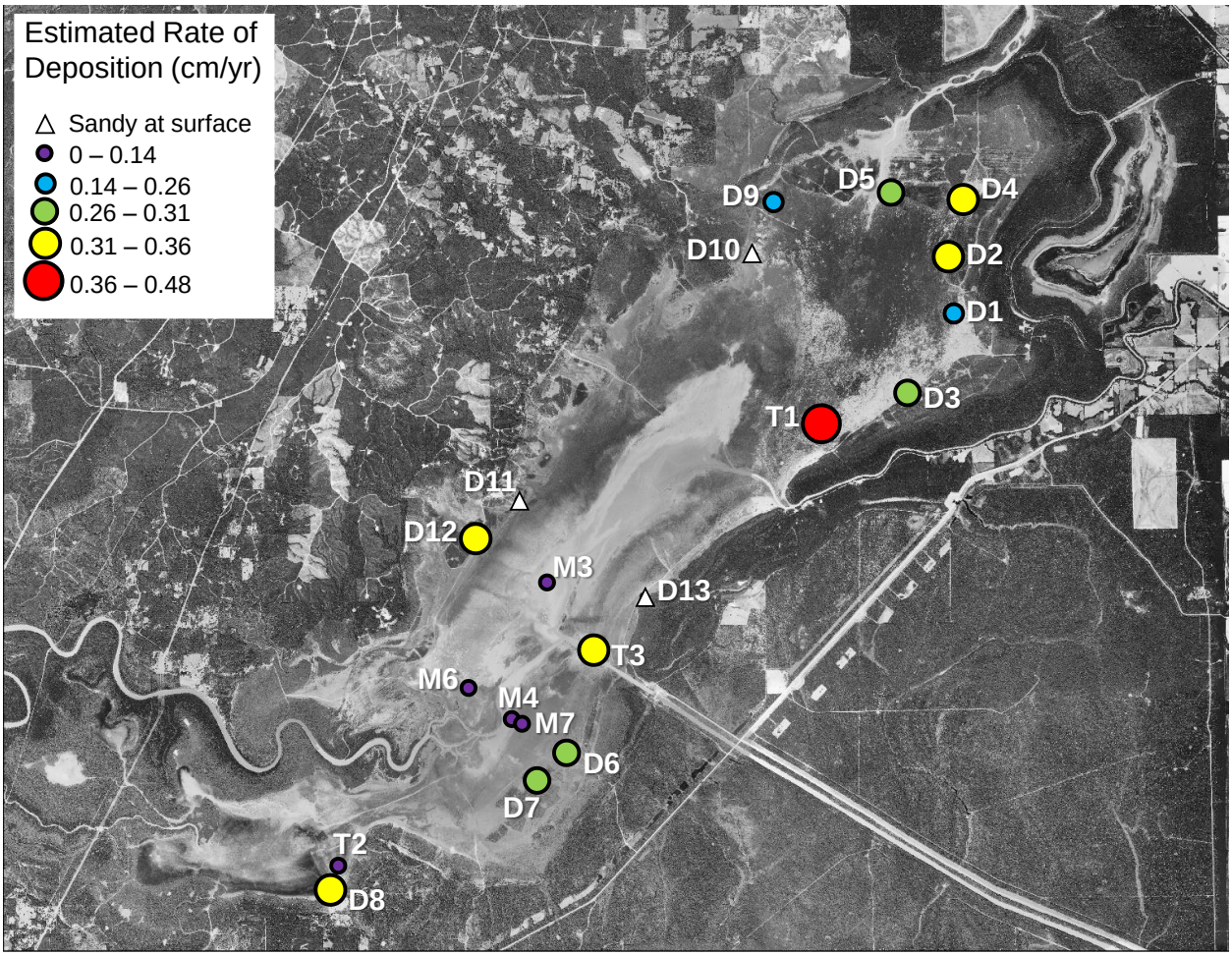

Figure 3.2. Rates of deposition estimated analysis of sediment profiles. Profiles labeled with "D" are from this study and are estimates for 1954-2012 using ^{137}Cs. Profiles labeled "sandy at surface" had insufficient ^{137}Cs to analyze. Profiles labeled with "M" are from Meriwether (2007) and are estimates for 1954-2006 using ^{137}Cs. Profiles labeled with "T" are from Tedford (2009) and are estimates for 1800 AD - present using ^{210}Pb. (USDA aerial imagery from 2007)

There was little indication of spatial variability in particle size, other than several clusters of sandy deposits (Figure 3.4). Two groups of sandy sediments occurred north of the canal (N, M, D13) and south of the canal (S, B, C). Another grouping of sandy sediments was at the north end of the lake (X, D10). One core, D11, was near the bluffs on the north side of the lake.

Discussion

^{137}Cs data suggests the rate of sedimentation is faster than previously believed by Russell (1942) as reported by Willis (2009), Brown (1943), Bruser (1995), and Willis (2009). All

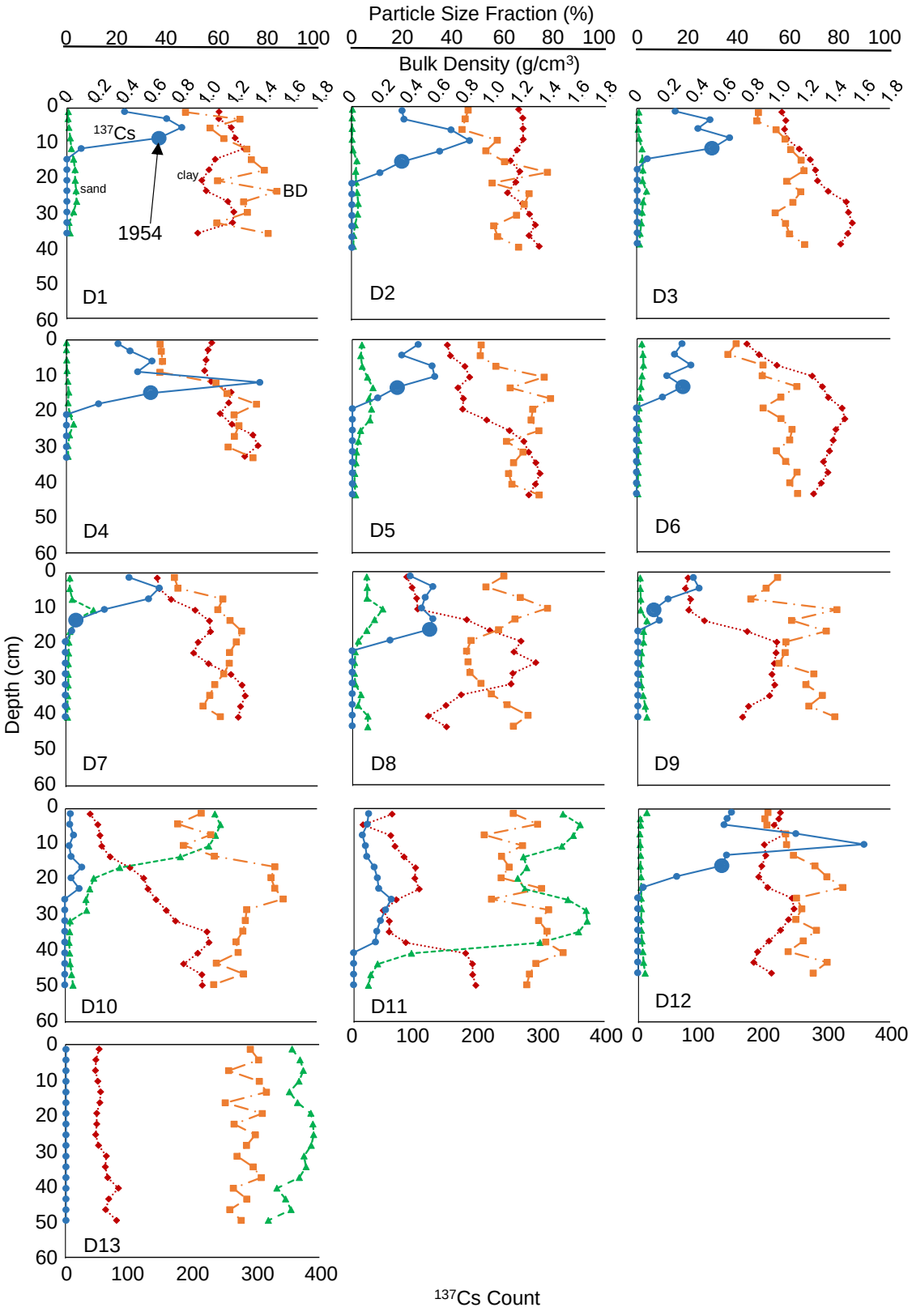

Figure 3.3. Particle size, bulk density, and ^{137}Cs counts in the Cs profiles.

Table 3.2. USDA Natural Resource Conservation Service soil textural classifications (NRCS 1993).

NRCS Textural Class	% of total
Silty clay	32.3
Clay	31.7
Silty clay loam	8.4
Sand	7.2
Silt loam	5.9
Loamy sand	5.5
Sandy loam	3.9
Loam	2.0
Sandy clay loam	1.6
Clay loam	1.2
Silt	0.2

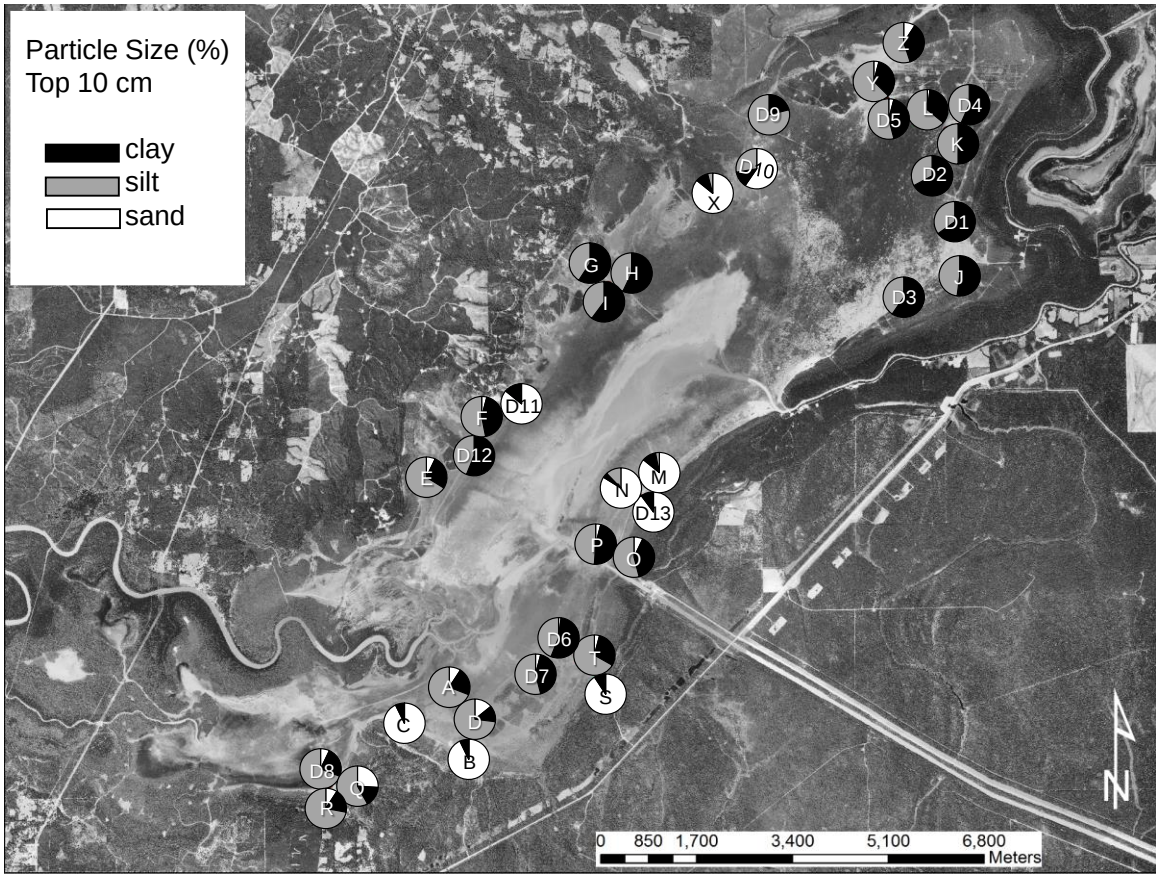

Figure 3.4. Particle size fractions for the top 10 cm of each core (USDA aerial imagery from 2007).

described sedimentation as negligible as a result of decreased connectivity with Mississippi River sediments. The results of this work suggest elevated sedimentation rates post-settlement but not increased sedimentation since the era of hydrologic alteration of the lake 40-60 years ago. The sedimentation rates for ~1800 AD – 2004 estimated by Tedford (2009) using ^{210}Pb dating are similar to those we obtained using ^{137}Cs (Table 3.3) with mean sedimentation rate of 0.32 cm yr^{-1} as compared to our 0.26 cm yr^{-1}. If this difference is insignificant, it may be because sedimentation has indeed been reduced by loss of connectivity to the Mississippi River, or it could be that sedimentation decreased in the past 58 years as farming practices and soil conservation have lessened sedimentation from the Little River.

Spatial variability of deposition was low, and variability among measurements did reveal a few interpretable spatial patterns in deposition (Figure 3.2). The highest deposition rates were at the southernmost part of the lake at the location of a historic ferry landing, and the lowest deposition rates were at the north end of the lake.

Table 3.3. Comparison of this study with two other studies of Catahoula Lake that also estimated sediment deposition rates.

Study	Time Period	Mean Sedimentation Rate (cm yr^{-1})	Mean Sedimentation Rate (t ha^{-1} yr^{-1})	Mean Sediment Load (t yr^{-1})
This Study	~1954 – 2012	0.3	25.2	204,000
Meriwether 2007	~1963 – 2004	0.1	14.9	121,000
Tedford 2003				
	~1800 AD – 2004	0.3	33.4	270,000
	~2535 YBP - ~1800	0.1	8.4	68,000
	~3900 YBP - ~2730	0.1	6.3	51,000
	~4100 YBP - ~3900	0.0	2.1	17,000

The presence of turbation from wave action, boats, grazing animals, vehicles, and even ducks complicates interpretation of ^{137}Cs horizons. Wave action, frequently re-suspending sediments and creating escarpments of varying elevations around the lake has been long known

(Brown 1943, Fisk 1944, Willis 2009, Tedford 2009). Cattle grazing occurred until 2001 (Willis 2009, Horst 2012) and bioturbation from wild hogs is also locally severe. Ducks foraging for tubers further disturbs sediments (Peters, Afton 1993). Catahoula Lake also experiences vehicular traffic in association with waterfowl hunting season. In 2000 a dredging operation between the canal and the input of the Little River disturbed the lake sediments, moving them to the side of the channel. This process displaced sediments and re-suspended them only to settle out later, which would possibly remove the horizons where ^{137}Cs was present and distribute the ^{137}Cs elsewhere. In general this activity may broaden the ^{137}Cs peaks, but will not likely change the position of the major ^{137}Cs horizons (Pennington et al. 1973; Ritchie, McHenry 1990). Our analysis was conservative in identifying 1954 as the basal horizon with substantial ^{137}Cs and assuming trace amounts below that were from turbation.

The lack of spatial pattern in deposition rates suggests that turbation redistributes sediment from its sources. For example, we did not find systematically different sediment deposition near the inlet of Little River, nor near other flowing waterways such as the diversion canal or the French Fork outlet. Therefore, it is difficult to ascribe the sources of sediment to either Little River (coastal plain), small tributaries to the west (coastal plain) or connection to the east (Mississippi River alluvial valley). Because the Little River is captive to the lake, its sediments are likely mostly deposited except during times of high flow or due to re-suspension. The Little River is likely the source of all sand in the current hydrologic regime, because only backwater flooding occurs from the LMAV side. Unfortunately, redistribution prevents a process-based conclusion about the sources of sediment or likely causes for elevated recent rates.

It is possible that the rate of sedimentation at Catahoula Lake could be a significant factor driving changes in vegetative community composition and structure. Sedimentation at Catahoula

Lake could be affecting water quality, plants, invertebrates, and wildlife in turn. Sediment may be burying the seeds of herbaceous plants, reducing total seedling emergence (Gleason et al 2003) and altering plant communities by impeding the re-colonization process of plants. (Rybicki, Carter 1986; Hartleb et al. 1993; Jurik et al. 1994; Wang et al. 1994). The heartier, woody vegetation is likely better adapted to deal with sediment. Increased sediment means a decrease in lake depth and duration of flooding through changing the topography of the lake bed, and as a result, the length of the growing period could change with increased sediment. These changes in depth also effect the amount of invertebrates present, an additional source of food to waterfowl.

Conclusions

Sedimentation at Catahoula Lake has been about 0.26 cm yr^{-1} for the past 60 years but may have decreased slightly after a peak sometime in the past about 200 years. Sedimentation is at a fairly uniform depth across the lakebed, suggesting redistribution after initial deposition.

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Chapter 4. Sediment Chemistry at Catahoula Lake, Louisiana

Introduction

The processes that control species composition and structure in wetland ecosystems are complex and include seasonality (Nilsson, Svedmark 2002), depth, and duration of flooding (Casanova, Brock 2000); nutrient dynamics (Bedford et al 1999); and other sediment chemistry. Catahoula Lake near Alexandria, Louisiana has remained a seasonally inundated lake for about 4,000 years (Tedford 2009) and has been experiencing an advancing front of woody, terrestrial vegetation into the lake bed for at least the last 60 years. It has become increasingly important to understand the processes that determine where the tree line ends and the more diverse herbaceous vegetation begins as important waterfowl habitat is lost. Processes controlling this expansion of woody vegetation are largely unknown but sedimentation may be playing a role (Shafroth et al 2002, Reisinger et al 2013). Anthropogenic alterations to watersheds including dam construction, levees, water control structures, and conversion of wetlands to agricultural lands through draining alter hydrology and sediment loads, threatening many of these ecosystems. (Toner, Keddy 1997; Nilsson, Berggren 2014). For example, more than 400,000 ha of Wisconsin wetlands are dominated by reed canarygrass (*Phalaris arundinacea*) due in large part to increased sediment input from erosion of agricultural lands filling in and flattening the heterogeneous topography of tussock sedge meadows (Zedler, Kercher 2004). As a substrate for plant growth, the chemical and physical composition of sediments can determine plant community structure and composition and changes in sediment sources can dramatically alter the ecosystem (Briggs et al 2005, Reisinger et al 2013).

Catahoula Lake is a complex wetland of international importance that is experiencing a shift in vegetation. Woody vegetation is encroaching into the lake bed and the rate of this expansion has increased since anthropogenic changes to the hydrology of the lake and nearby

rivers (Chapter 2). Concurrently, sedimentation has increased relative to pre-settlement rates (Tedford 2009, Chapter 3), which suggests it may be playing a role in the shifting lake ecosystem. If the sources of sediment are different now than historically, differences in their chemical and physical nature may be contributing to changes in the ecosystem beyond simply raising the lakebed elevation. In addition, any differences in the composition of surficial and buried sediments may reveal shifts in sources that may be related to woody expansion.

There are three likely major sources of sediment entering Catahoula Lake, with distinct differences among them that can aid in tracing sources: the Western Coastal Plain, Southern Mississippi River Alluvium, and Red River Alluvium (Weindorf 2008). The Western Coastal Plain is composed of tertiary and cretaceous mixed marine and alluvial sediments that are loamy or clayey with smectitic or mixed smectitic and kaolinitic mineralogy (Autin, Aslan 2001; Weindorf 2008) and are acidic due to weathering and leaching of basic cations (Autin, Aslan 2001). Southern Mississippi River Alluvium is composed of sandy to clayey fluvial Holocene deposits with smectitic mineralogy and high base saturation (Weindorf 2008). Red River Alluvium is composed of sandy to clayey fluvial deposits of Holocene to late Pleistocene floodplains and terraces with smectitic mineralogy (Weindorf 2008), but lower in montmorillonite than Mississippi River alluvium (Taggart, Kaiser 1960). These varying compositions are useful as tracers of source material for sediments deposited at Catahoula Lake.

Aside from usefulness as tracers of origin, the chemical nature of sediments may be important for ecosystem processes. Changes in macronutrients-- nitrogen, phosphorus, and potassium-- in the sediments at Catahoula Lake could be particularly influential in plant communities (Koerselman, Meuleman 1996; Bedford et al 1999). Land-use practices such as

fertilization are frequent causes of increased nutrient loading in agricultural landscapes (Saunders, Kalff 2001).

The overall objective is to understand the elemental composition of sediments at Catahoula Lake and determine whether there are any patterns that indicate physical processes controlling the lake or chemistry affecting the ecosystem. The first specific objective is to use the chemistry, particle size, and pH of sediments to evaluate whether sediment sources may have changed in the recent past in association with changing land use and with hydrologic management. The second specific objective is to investigate the plant active elements to determine whether changes in nutrient status may be related to ecosystem changes.

Methods

Field Methods

We collected 37 sediment profiles for elemental analysis. The first 12 profiles were collected to a depth of 1 meter with a Giddings Probe soil corer in fall 2011. Another 25 profiles were collected to a depth of 0.50 meters in 2012. Twelve of these were collected by digging pits and cutting slices out of the profile, and 13 were collected in 10 cm diameter aluminum tubes. Profiles were sampled in the zone of expansion of water-elm, near, elevation 10.4 m. These depths of sampling correspond to approximately 167 years of deposition according to sedimentation rates estimated by Tedford (2009).

Laboratory Methods

In the laboratory, the Giddings probe and pit profile samples were divided into 5 cm increments and the aluminum tube profiles were divided into 3 cm increments (for ^{137}Cs analysis, Chapter 3). All samples were then oven-dried to 105° C, disaggregated with a Humboldt soil grinder or mortar and pestle and passed through an ASTM number 10 sieve.

The samples from the top 15 cm of each profile were tested for elemental analysis using inductively coupled plasma atomic emission spectrometry (ICP-AES) by the LSU Soil Testing and Plant Analysis Lab. We prepared the samples using EPA method 3050B for acid digestion. This method uses HNO_{3-} and HCl with heat to dissolve almost all recoverable elements other than those bound in silicate structures (Chen, Ma 1998). We included a blank in every other digested batch of 16 samples to correct for any contamination that may have occurred during digestion. The ICP analysis provided concentrations of aluminum, boron, barium, beryllium, calcium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorus, lead, sulfur, silicon, titanium, vanadium, and zirconium.

Another elemental analysis was run on all samples at all depths using portable x-ray fluorescence (PXRF) spectrometry, a non-destructive technique that requires minimal preparation (oven-dry, disaggregated sediment samples). Samples were scanned with the DELTA Handheld PXRF Analyzer with a tantalum tube. Every ten scans we calibrated the machine and scanned two NIST standards (NIST 2781, NIST 2702). The PXRF analyzer provided concentrations of silver, arsenic, barium, cadmium, calcium, chlorine, cobalt, chromium, copper, iron, mercury, iodine, potassium, manganese, molybdenum, nickel, phosphorus, rubidium, lead, antimony, selenium, tin, strontium, sulfur, titanium, zinc, and zirconium. However, for some elements the PXRF reported large errors or produced data that were poorly correlated with ICP. Therefore, we did not use elemental data for which the error reported by the instrument exceeded the concentration, or for which correlation with ICP was less than $R^2 = 0.40$ (Appendix B). The remaining, high-quality data were for barium, calcium, cobalt, chromium, iron, potassium, manganese, lead, rubidium, strontium, titanium, and zirconium.

Total carbon and nitrogen were determined by the LSU Wetland Biogeochemistry Analytical Services using a Costech 1040 CHNOS Elemental Combustion system. Sediment profile samples were combined and mixed to make representative 9-10 cm samples, depending on whether the profiles were originally divided into 3 or 5 cm increments. Approximately 8-9 mg of sample was weighed into a tin capsule, which was crimped and sealed for maximum combustion.

Sediment pH was measured using 6-9g samples from every 10 cm of each profile to a depth of 0.50 m using a Thermo Scientific 3-Star Plus bench-top pH meter. Samples were made into a 1:1 slurry with deionized water and measured after 15 minutes as described by Thomas (1996).

Statistical Methods

The goal of the first set of analyses was to determine whether natural groupings of elements and physical properties existed in samples, which could be indicative of sediment sources. We analyzed the elemental concentrations and physical characteristics using principle component (PCA) and hierarchical cluster analyses (PROC FACTOR and PROC CLUSTER in SAS 9.3). Variables in both analyses were depth, total nitrogen, total carbon, percent sand, percent clay, pH, barium, calcium, cobalt, chromium, iron, potassium, manganese, lead, rubidium, strontium, titanium, and zirconium concentrations for all profile samples to 0.50 meters (n = 420). Prior to analysis, all variables were standardized (value less the mean of all values, divided by standard deviation of all values) to ensure consistent scales and Euclidean distance was used in all multivariate procedures. For the PCA, we used the scree plot and broken stick criterion (McCune, Grace 2002) to test for significance of components. For the cluster analysis, we used peaks in the pseudo-F statistic to determine how many clusters existed.

Our next goal was to determine whether sediments deposited since 1954, or those that contained ^{137}Cs (Chapter 3), were different in composition than the pre-1954 sediments or those without ^{137}Cs. We analyzed an abbreviated dataset (n=159) that consisted of only the 13 larger profiles collected for ^{137}Cs analysis. We removed the sandy profiles, D10, D11, and D13, which had no significant ^{137}Cs in their profiles, because it was impossible to discern the recent sediments in those samples. The ^{137}Cs counts were changed to a yes/no variable based on the presence or absence of ^{137}Cs. We used an F-test (PROC GLM in SAS 9.3) to test the null hypothesis of no relationship between independent variables ^{137}Cs presence and percent clay, with the dependent variables total nitrogen, total carbon, barium, calcium, cobalt, chromium, iron, potassium, manganese, lead, rubidium, strontium, titanium, and zirconium content.

Last, we analyzed carbon and nitrogen to determine whether any significant differences existed with depth. We analyzed C:N as an independent variable with the dependent variables total nitrogen, total carbon, and depth using a linear model (PROC GLM, SAS 9.3).

Results

The scree plot and broken-stick criterion agreed that sediments were best described by two components in the PCA (Figure 4.1, Table 4.1). The first component was dominated by particle size. It was highly positively correlated with clay and highly negatively correlated with sand. This component was also highly positively correlated with barium, calcium, cobalt, chromium, iron, potassium, manganese, lead, rubidium, strontium, and titanium (Table 4.2); most of these elements are cations associated with clay particles. Component 2 was highly positively correlated with depth, pH, calcium, potassium, and manganese, and negatively correlated with nitrogen, carbon, lead, and zirconium (Table 4.2). The strongest correlations—

Table 4.1. Eigenvalues of principal components analysis of physical and chemical variables for all profile samples to 0.50 m depth.

Eigenvector	Eigenvalue	Cumulative R^2	Broken Stick Eigenvalue
1	9.52	0.53	3.50
2	3.66	0.73	2.50
3	1.23	0.80	2.00
4	0.93	0.85	1.66
5	0.57	0.88	1.41
6	0.51	0.91	1.21
7	0.48	0.94	1.05
8	0.33	0.96	0.90
9	0.27	0.97	0.78
10	0.20	0.98	0.67
11	0.10	0.99	0.57
12	0.06	0.99	0.48
13	0.05	0.99	0.39
14	0.03	1.00	0.31
15	0.03	1.00	0.24
16	0.02	1.00	0.18
17	0.02	1.00	0.11
18	0.01	1.00	0.06

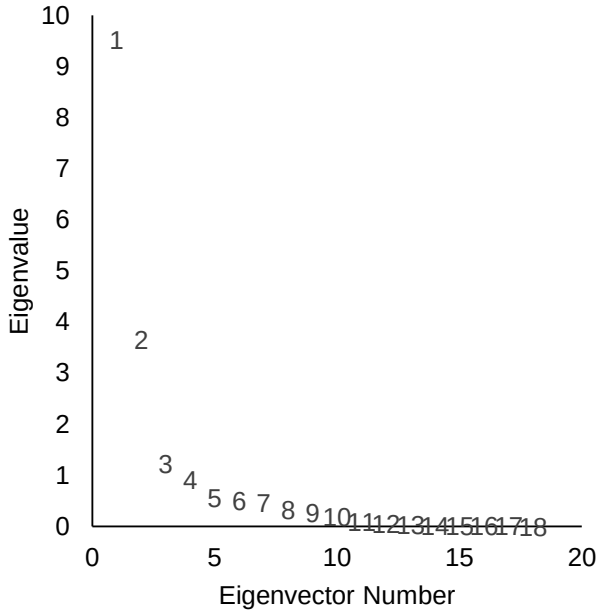

Figure 4.1. Scree plot for principal components analysis of physical and chemical variables for all profile samples to 0.50 m depth.

Table 4.2. Loadings of variables on principal components 1 and 2.

Variable	Loading on Component	
	1	2
depth	0.15	0.67
sand	-0.86	0.33
clay	0.93	0.01
pH	0.09	0.73
Ba	0.97	0.02
C	0.34	-0.78
Ca	0.81	0.47
Co	0.87	0.06
Cr	0.95	0.03
Fe	0.84	0.11
K	0.79	0.39
Mn	0.61	0.45
N	0.49	-0.76
Pb	0.45	-0.59
Rb	0.97	0.00
Sr	0.79	0.19
Ti	0.88	-0.30
Zr	0.04	-0.57

depth, pH, and negative carbon and nitrogen-- indicate a component describing depth below the surface.

The hierarchical cluster analysis resulted in a dendrogram that is also dominated by particle size. There were two large clusters with 332 members and 82 members with a distance between clusters of about 0.98 (Figure 4.2). The smaller cluster was positively correlated with sand and negatively correlated with clay, carbon, nitrogen, barium, calcium, cobalt, chromium, iron, potassium, manganese, lead, rubidium, strontium, zirconium, and titanium. The larger cluster was positively correlated with clay, barium, chromium, rubidium, and titanium; and negatively correlated with sand. These two clusters then further separated out into less interpretable clusters with smaller distances between clusters.

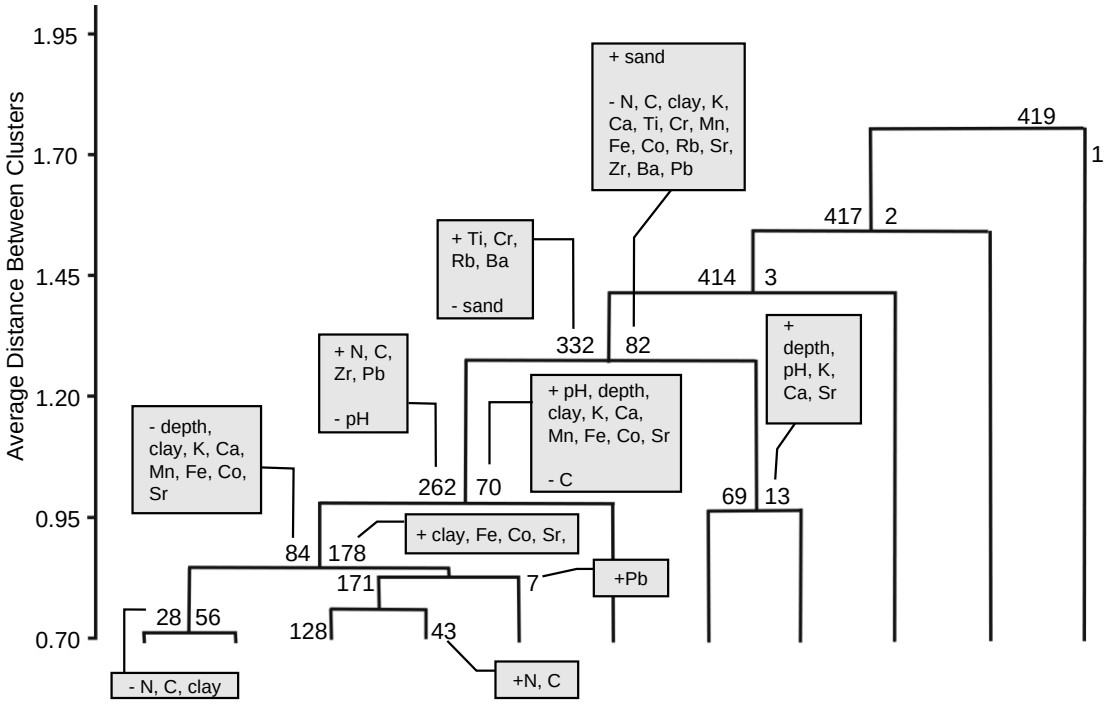

Figure 4.2. Dendrogram trimmed at 0.69 created by cluster analysis of the variables depth, total nitrogen, total carbon, pH, percent sand, percent clay, and elemental concentrations for all profile samples.

Some elemental concentrations varied between surficial, ^{137}Cs-containing sediment layers and deeper sediments, and all elemental concentrations varied with clay content (Table 4.3). Nitrogen (See iii in Figure 4.3), carbon (See i in Figure 4.3), titanium (See v in Figure 4.5), zirconium (See vii in Figure 4.5), barium (See v in Figure 4.4), and lead (See ix in Figure 4.3) occurred significantly more in the top ~14 cm of sediment where ^{137}Cs is present. Potassium (See v in Figure 4.3), calcium (See vii in Figure 4.3), manganese (See iii in Figure 4.4), and strontium (see iii in Figure 4.5) occur significantly more in the older sediments, or where ^{137}Cs is absent. Chromium (See ix in Figure 4.4), iron (See i in Figure 4.4), cobalt (See vii in Figure 4.4), and rubidium (See i in Figure 4.5) show no significant difference between ^{137}Cs present and absent layers. All of the analytes increased significantly with clay content except zirconium. The relationships between zirconium and clay content and titanium and clay content were non-linear. In the clay-normalized full data set (n=420), again some elemental concentrations varied with

Table 4.3. Significance ($p<0.05$; $n=194$) of relationship between variables and presence of ^{137}Cs and clay content from analysis of profiles D2-D9, and D13.

Element	Presence of Cs^{137} (f-value)	Clay content (f-value)
Ba	0.0211	<0.0001
C	<0.0001	<0.0001
Ca	<0.0001	<0.0001
Co	0.3863	<0.0001
Cr	0.5244	<0.0001
Fe	0.2232	<0.0001
K	<0.0001	<0.0001
Mn	<0.0001	<0.0001
N	<0.0001	<0.0001
Pb	<0.0001	<0.0001
Rb	0.3493	<0.0001
Sr	<0.0001	<0.0001
Ti	<0.0001	<0.0001
Zr	<0.0001	0.0566

depth. Carbon (See ii in Figure 4.3), nitrogen (See iv in Figure 4.3), lead (See x in Figure 4.3), titanium (See vi in Figure 4.5), and zirconium (See viii in Figure 4.5) decreased with depth as they did in the non-normalized data. Calcium (See viii in Figure 4.3) and manganese (See iv in Figure 4.4) exhibited the same relationships as the non-normalized data, increasing with depth. Iron (See ii in Figure 4.4), cobalt (See viii in Figure 4.4), chromium (See x in Figure 4.4), and rubidium (See ii in Figure 4.5) still showed no significant relationship with depth. Potassium (See vi in Figure 4.3), barium (See vi in Figure 4.4) and strontium (See iv in Figure 4.5) were more homogenous with depth than before the data were normalized.

Additionally, ICP-only (top 15 cm) data (Figure 4.6) revealed aluminum, magnesium, vanadium, phosphorus, boron, and zinc are significantly positively correlated with clay content.

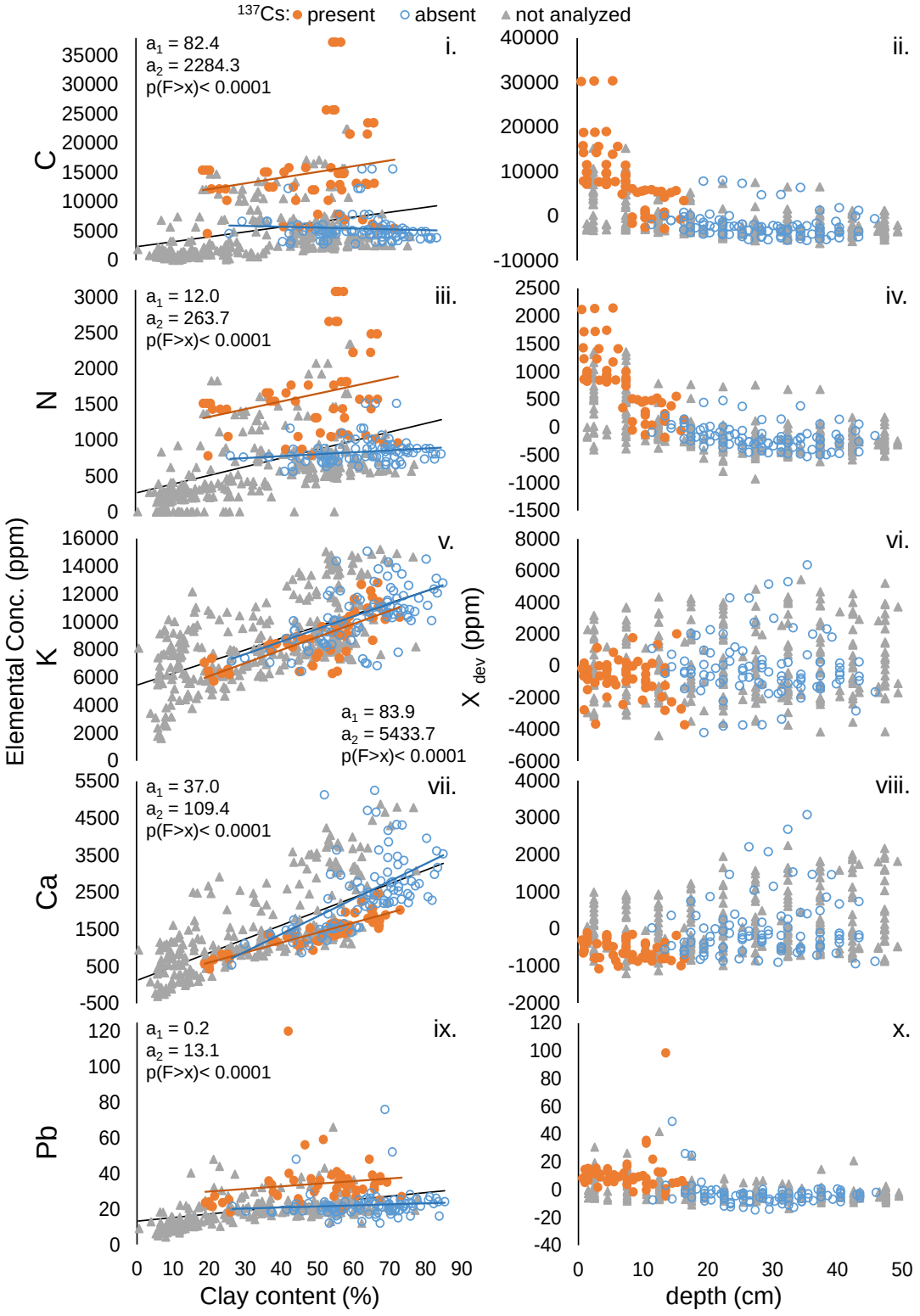

Figure 4.3. Scatterplots of correlations between elemental concentrations and clay content (i, iii, v, vii, and ix) and between elemental concentrations normalized for clay content and depth (ii, iv, vi, viii, and x). Normalized clay plots were created using the equation $X_{dev} = X_{obs} - a_1 + a_2 clay$.

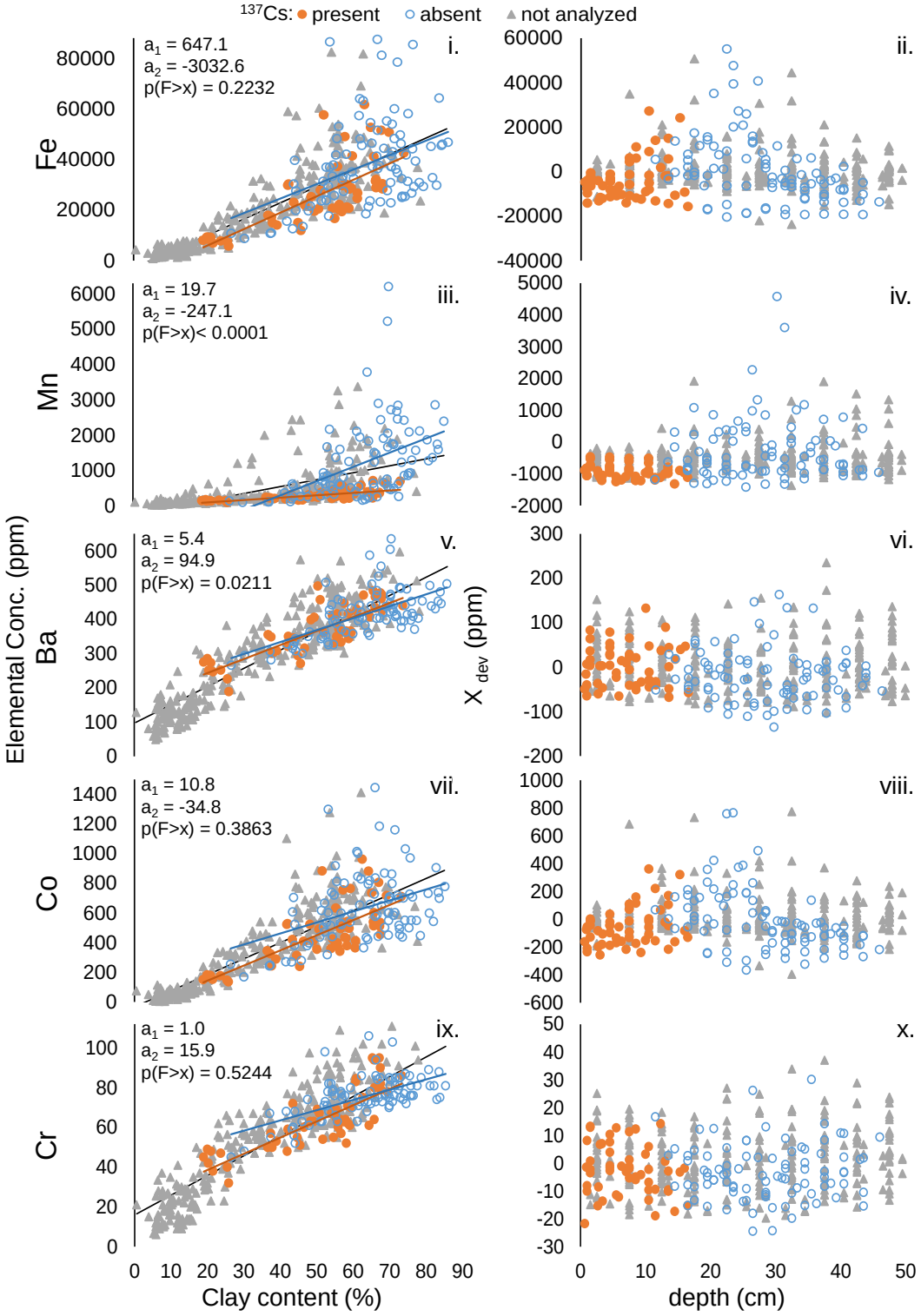

Figure 4.4. Scatterplots of correlations between elemental concentrations and clay content (i, iii, v, vii, and ix) and between elemental concentrations normalized for clay content and depth (ii, iv, vi, viii, and x). Normalized clay plots were created using the equation $X_{dev} = X_{obs} - a_1 + a_2 clay$.

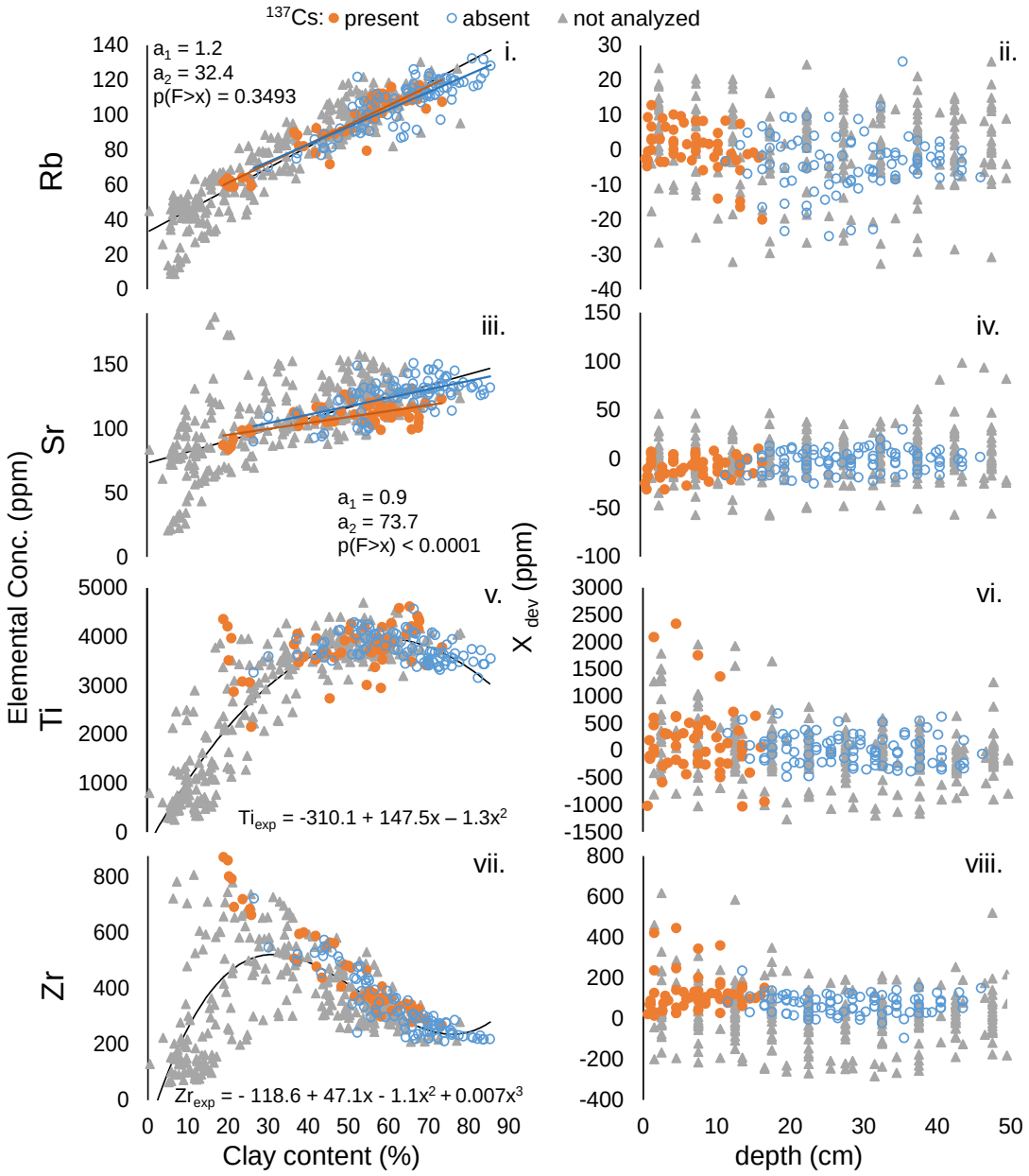

Figure 4.5. Scatterplots of correlations between elemental concentrations and clay content (i, iii, v, vii, and ix) and between elemental concentrations normalized for clay content and depth (ii, iv, vi, viii, and x). Normalized clay plots were created using the equation $X_{dev} = X_{obs} – a_1 + a_2 clay$.

Calcium, sodium, nickel, sulfur and silicon show no significant correlation with clay content. Because the PXRF was unable to detect these elements with sufficient precision and ICP analysis only went to 15 cm depth, we could not determine relationships with depth or compare recent sediments with older sediments.

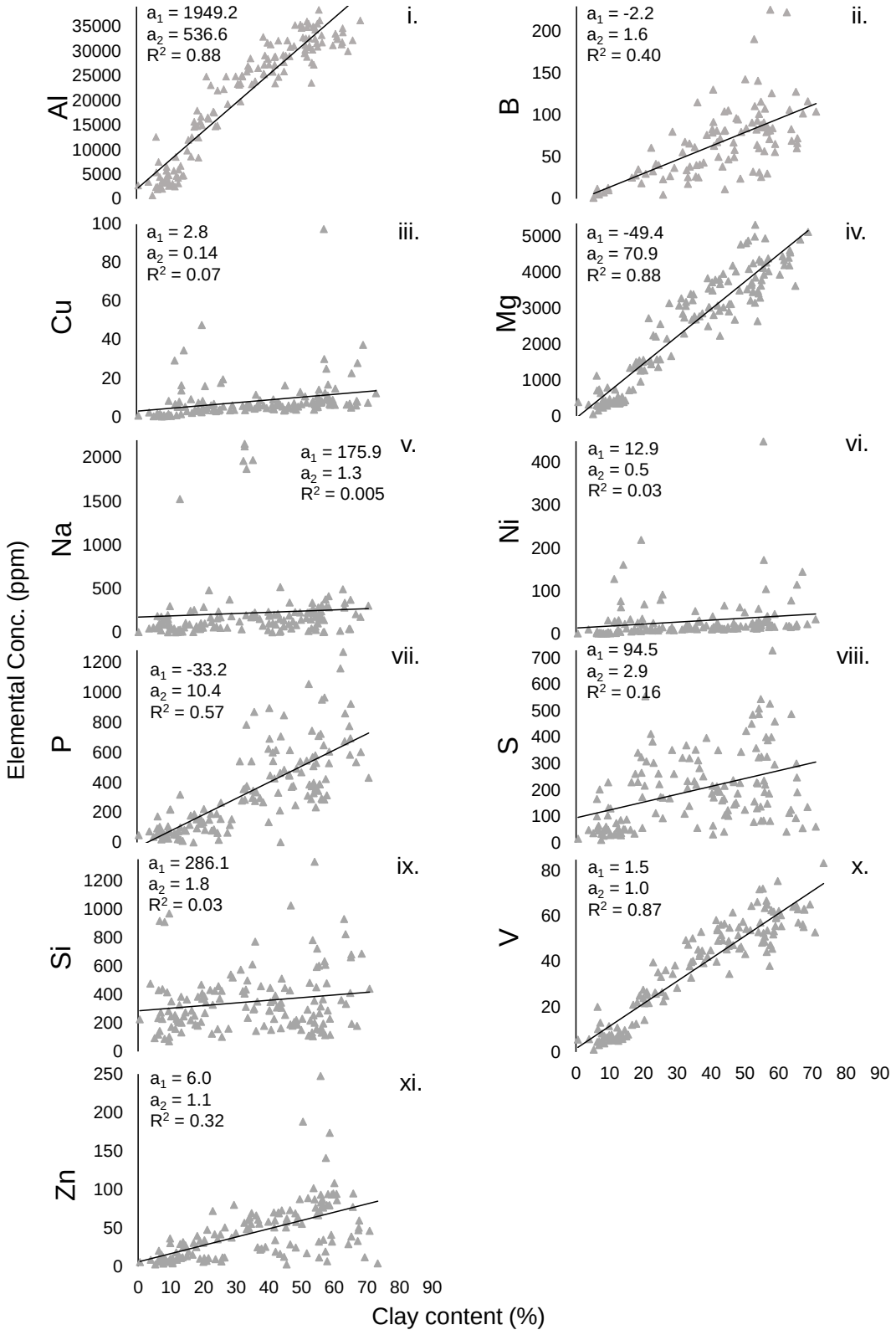

Figure 4.6. Scatterplots of correlations between elemental concentrations and clay content for elements analyzed with ICP at 0-15 cm depth.

Total carbon was mean 0.56% by mass and ranged from 0 to 37.28 g kg^{-1}. Total nitrogen was mean 0.08% by mass and ranged from 0 to 3.08 g kg^{-1}. The mean C:N was 5.96 and ranged from 0 to 15.75. Analyzing C:N with depth indicated that carbon was marginally significantly more recalcitrant with depth (p= 0.06) (Figure 4.7) but overall was relatively labile throughout the top 50 cm. Combining these measured concentrations with sediment deposition rate of 0.3 cm yr^{-1} (Chapter 3) leads to an estimate of carbon and nitrogen sequestration at Catahoula Lake of 10.35 g m^{-2} yr^{-1} and 1.51 g m^{-2} yr^{-1}, respectively, and potassium is being sequestered at a rate of 7.32 g m^{-2} yr^{-1} (Table 4.4). Phosphorus sequestration estimates were calculated using the ICP data, restricting estimates to the top 15 cm of the profile, and is thus estimated as being sequestered at a rate of 0.76 g m^{-2} yr^{-1} (Table 4.4).

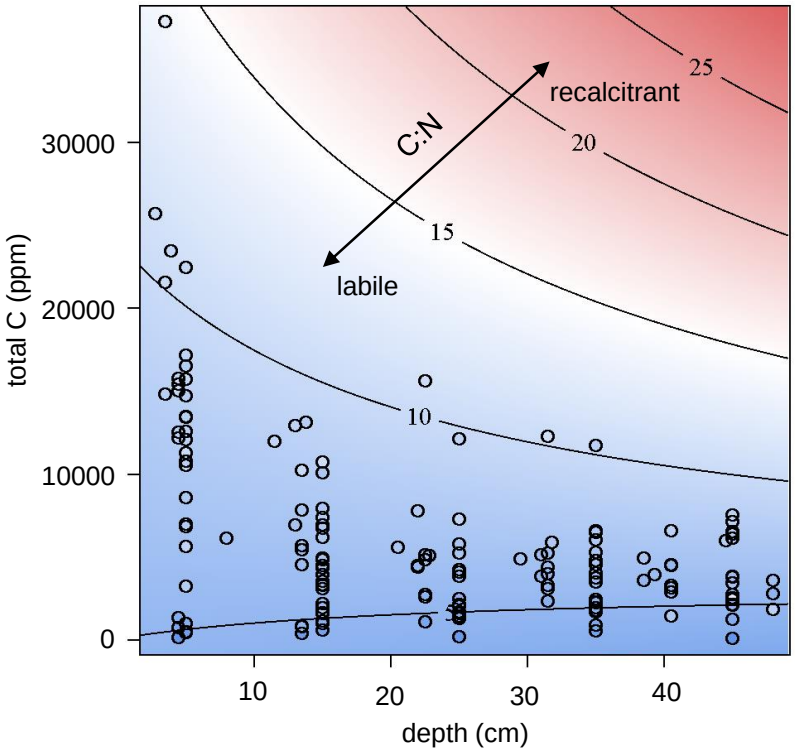

Figure 4.7. Relationship between total carbon, depth and C:N ratio from analysis of all profiles at 10 cm increments (n=166).

Table 4.4. Sequestration of plant active elements at Catahoula Lake.

Element	Rate of Sequestration	
	(t/yr)	($g/m^2/yr$)
C	837.84	10.35
N	122.61	1.51
P	61.31	0.76
K	592.62	7.32

The pH of surface sediments was less than 5 for all but two samples and was below 4 for two samples. Variations of pH revealed two groups (Figure 4.8). The first group is characterized by pH below 5.7 throughout the profile and little variation with depth. The second group is characterized by pH that increases with depth to exceed 5.7. Group 1 is indicative of highly weathered, base-poor sediments while group 2 is indicative of younger, alluvial sediments.

The pH group membership of these profiles shows some indication of spatial variation consistent with Little River or other coastal plain sediment sources in southwest and Mississippi River alluvial sediments in the northeast (Figure 4.9). Group 1 (acid throughout) sediments dominate on the western shore of the lake, and just south of the diversion canal. Group 2 sediments (neutral at depth) dominate on the north end of the lake, and just north of the diversion canal. Regardless of group membership, all sediments are acid at the surface in the recent, Cs-bearing layer.

Discussion

Overall, there is no evidence from either the PCA or cluster analysis that there are distinct classes of sediments in the lake not pertaining to particle size or depth. The strongest variables loading on the second component of the PCA— positive depth, pH, and negative C, N, and Pb – indicate sediments at depth of higher pH and the conversely, surficial sediments high in organic matter fresh from recent assimilation. The C:N ratio indicates this organic matter is not

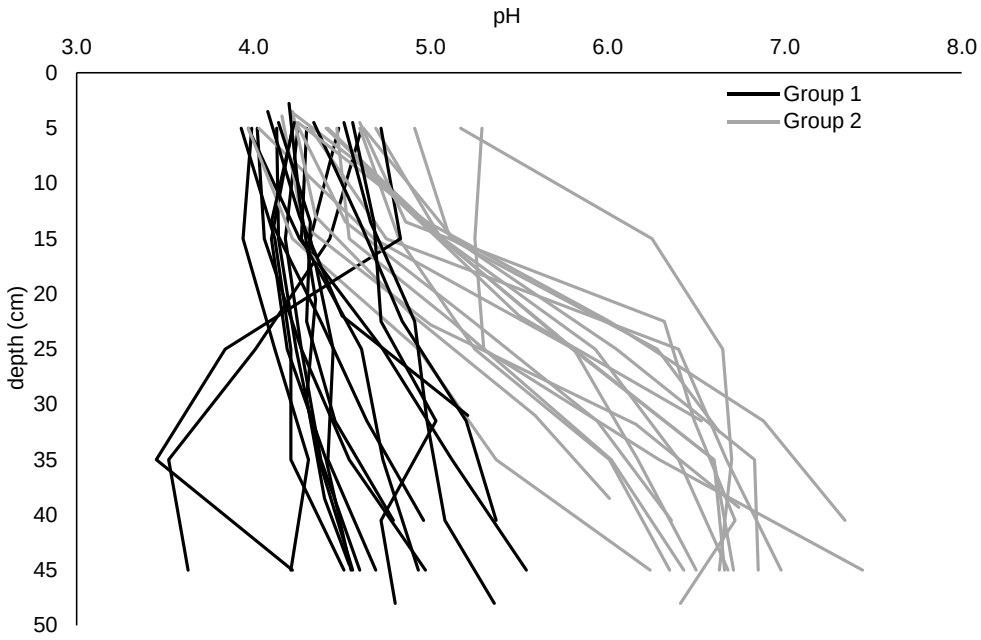

Figure 4.8. Scatterplots of pH with depth for all profiles. Lines denote group membership for each profile.

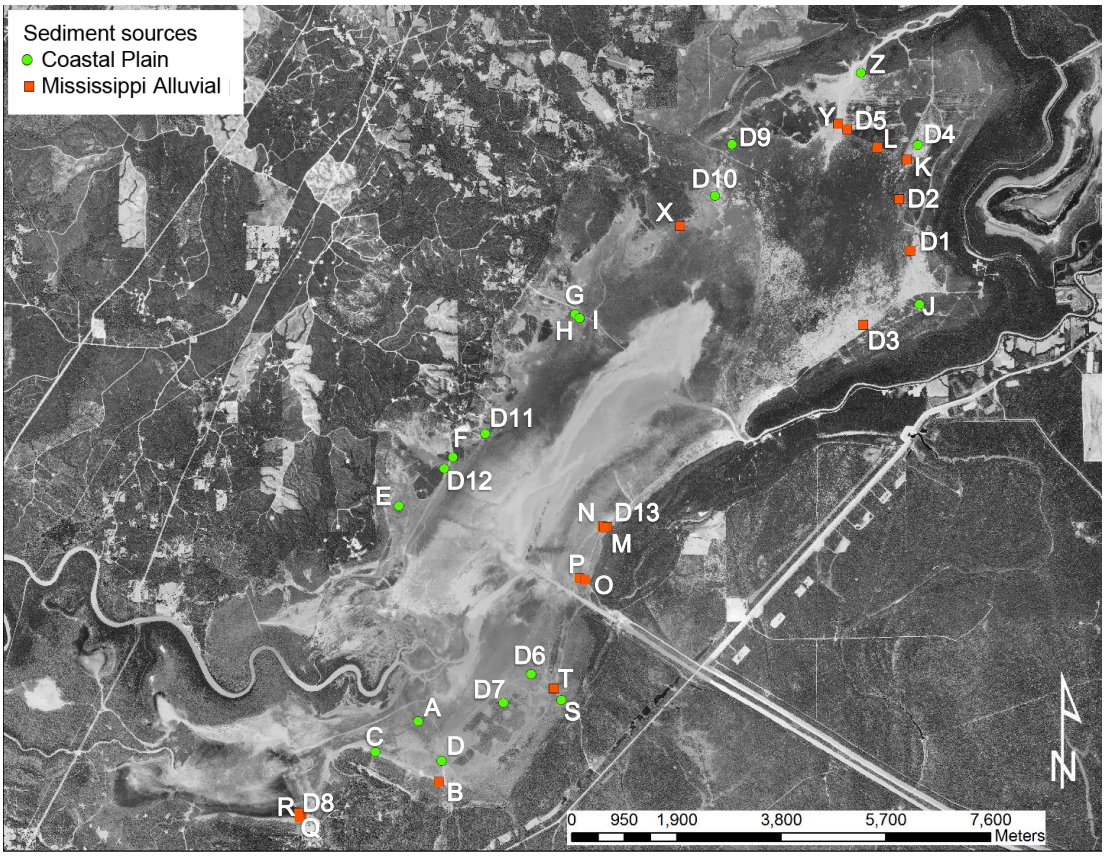

Figure 4.9. pH group membership—indicating likely sources of sediments at 20-50 cm depth.

accumulating in the lake, and is likely mainly mobilized and removed during drawdown instead of being sequestered. The strong negative association with lead in the deeper sediments indicates surficial lead, which is already well known to be the result of lead shot from waterfowl hunters (Peters, Afton 1993). The reasons for the other variations with depth are less obvious, and suggest there has been a temporal shift in sediment at Catahoula Lake. The hierarchical cluster analysis was less useful for analysis of sediments as it complicates the relationship between depth and particle size. The orthogonality of PCA allowed depth and particle size to exist together.

Generally higher concentrations of calcium and potassium below the surficial sediments may be indicative of a historically greater input of Mississippi River alluvial sediments with Coastal Plain sediments dominating more recently. Mississippi River sediments are high in smectites, or 2:1 clays, which have high cation exchange capacity. They are also relatively unweathered so they retain high concentrations of basic cations like Ca^{2+} and K^{+}, causing their more basic pH. Coastal plain sediments are higher in kaolinite, or 1:1 clays, which form by weathering in situ over a long time during pre-glacial time (Sionneau 2008). These sediments are base poor, and therefore more acidic (Milne, Earley 1958; Autin, Aslan 2001).

The high concentration of zirconium and titanium only at the surface suggests a recent change in the source of sediment in the past ~50 yr. The change may be an increase in dominance of coastal plain sediments. Pleistocene sediments are enriched in zirconium and titanium, which may indicate recent deposition of coastal plain sediments. However, both zirconium and titanium are known to be highly resistant to weathering and their mobility is still not well understood (Milnes, Fitzpatrick 1989; Hodson 2002). Alternatively, zirconium and titanium enrichment could indicate an influx of sediments from western sources via the Red

River. Zirconium concentration is dependent on the presence of zircon, its main mineral form in rocks and sediments (Milnes, Fitzpatrick 1989), which is present in higher amounts in sediments of the Red River compared to the Mississippi River (Davies, Moore 1970; Mange, Otvos 2005). Titanium, which is associated with high zirconium in the clay fraction of sediments (Milnes, Fiztpatrick 1989), also is enriched in sediments from central Texas which were derived between 10,000 and 7,000 BP (Davies, Moore 1970). It may be possible connectivity to the Red River has been maintained more than has connectivity to the Mississippi River, because the Old River Control Structures and incision of the upper Atchafalaya River have reduced the backwater effect into Catahoula Lake (Willis 2009).

The increase in manganese with depth could be indicative of translocation during reducing conditions. Manganese is subject to changes in oxidation-reduction conditions that affect plant availability and solubility. When oxidation is occurring, manganese is immobile in sediment, but it is released into an aqueous phase during reducing conditions (Gambrell 1994, LaForce et al 2002) and may be translocated down the profile (Linnik, Zubenko 2002).

In addition to evidence in the depth-dependent variation in zirconium, calcium, and potassium, the pH data suggested two sources of sediment deposition at Catahoula Lake. In general, sediments were more acidic at the surface, which might indicate effects of weathering and organic matter, but organic matter is low and acidity at depth seems unlikely to be the product of weathering in situ because of sediment mobility and frequent reducing conditions. Therefore, we interpret acidity as being inherited from parent sediment material. Group 1 sediments (acid throughout) are consistent with the chemistry of the coastal plain. The sediment load carried by the Little River, indicated by Una and Urbo series soils just upstream from Catahoula Lake, both include very strongly acid horizons (4.5-5.0, NRCS 1993) and consist of

highly weathered Coastal Plain parent materials. Group 2 (neutral at depth) sediments are consistent with the sediment load carried by the Mississippi River and would include the Sharkey and Forestdale series soils. These series both include slightly acid (6.1-6.5) horizons near the surface, with slightly alkaline sediments (7.4-7.8) deeper sediments (NRCS 1993).

Thus, it appears that coastal plain sediments have dominated the lake for about 60 years (i.e., the same depth and same timeframe as ^{137}Cs deposition) at the expense of Mississippi River sediments. This change is consistent with the gradual loss of connectivity to the Mississippi and Red rivers via hydrologic modification such as navigation locks on the Black River and channelization and base level lowering of the Atchafalaya River (Willis 2009). On the other hand, the Little River is captive and all sediments must at least transit Catahoula Lake. It therefore appears that the decrease in sediment delivery to the lake over the past ~60 yr (Chapter 3) is more likely a result of lost connection to the Mississippi and Red rivers than decreases from the Little River.

Carbon and nitrogen decrease with depth at Catahoula Lake, showing larger amounts at the surface where fresh organic matter exists, but very little storage of carbon and nitrogen in the lower sediments. Carbon sequestration is very low at Catahoula Lake at just 10.4 g m^{-2} yr^{-1}. Mitsch et al (2010) compiled results of carbon sequestration studies from various types of wetland ecosystems and found a wide range from 8 g m^{-2} $year^{-1}$ in a high-latitude peat land (Ovenden 1990) to 260 g m^{-2} $year^{-1}$ in a humid tropical wetland in Costa Rica (Bernal, Mitsch 2008). Using C:N ratios we can also determine the source of this carbon (Das et al 2008, Kenney et al 2011). C:N ratios at Catahoula Lake are also low with mean 6.07, which is within the range of ~4-12 characteristic of primary producers like algae and phytoplankton or macrophytes (Das et al 2008).

Total nitrogen in the sediments of Catahoula Lake is low, which may be indicative of rapid denitrification and uptake of nitrogen by plants (Clarke, Wharton 2001) or simply low nitrogen loading. Howard-Williams (1985) reported total nitrogen in the top 20 cm of the sediments of several different wetland types to range between 370–6380 kg ha^{-1}. At Catahoula Lake it is an estimated 1200 kg ha^{-1}. The average percentage of total nitrogen in sediments at Catahoula Lake (0.08%) is comparable to low energy, temperate streams found in lowland England that range from 0.02% - 0.52% (Clarke, Wharton 2001).

There has been little work done to evaluate edaphic relationships between sediments and water-elm or swamp-privet that would aid in interpreting the sediment chemistry results in terms of their effects on expansion of woody vegetation in Catahoula Lake. Patterson (1997), concluded that water-elm was positively correlated to high exchangeable potassium, low calcium, and high pH; and that swamp-privet was positively correlated with high pH and Red River alluvium rather than Mississippi River alluvium. Rayner (1974), on the other hand, found that soils of mostly -pure stands of water-elm in South Carolina were very low in pH, around 4.4-4.8 and low in nutrients and basic cations. Given the contradictions in these findings, it is difficult to conclude whether a shift to dominance of coastal-plain sediments may favor establishment of these species. However, the conditions of Catahoula Lake are trending toward those typical of pure water-elm in South Carolina.

There are strengths and weaknesses of both of our two elemental analysis methods, ICP and PXRF. The PXRF has difficulty detecting low atomic number elements, particularly those below potassium (Migliori 2011). The lack of homogeneity of efficiency for some elements is also a concern (Kalnicky, Singhvi 2001; Zhu 2011). However, the instrument we used is capable of quick, in-situ analysis of total titanium, barium, lead, potassium, calcium, chromium, iron,

cobalt, and manganese, and with results highly correlated with ICP (Appendix B). Although ICP is generally accepted as the superior method for analysis of elemental concentration, it is not a total analysis as it is limited by the digestion method used on samples (Soltanpouri 1996). We used US EPA method 3050B, which is generally satisfactory for digesting recoverable silver, arsenic, barium, beryllium, cadmium, chromium, copper, mercury, manganese, molybdenum, nickel, lead, antimony, selenium, zinc, aluminum, calcium, iron, potassium, magnesium, and phosphorus (Chen, Ma 1998). However, this digestion method is incomplete and some silicate minerals and phosphorus are not dissolved. (Chen, Ma 1998; Richardson, Reddy 2013; Gambrell 2013; Soltanpour 1996). Thus, elements bound in silicate structures and phosphorus are likely underestimates of total concentration but relatively better as estimates of exchangeable concentrations.

The findings of this research point to two needed research projects. First, further study of phosphorus at Catahoula Lake would be of great benefit in understanding nutrient dynamics. The PXRF was unable to give us precise results for phosphorus and ICP was only performed on the top 15 cm of all profiles. Because phosphorus is an important limiting nutrient in many ecosystems, it would be useful to gather data with greater depth to understand whether its concentrations have changed over time. Second, future research at Catahoula Lake should also include a study of the mineralogy of sediments. Although elemental concentrations like those of calcium, potassium, titanium, and zirconium can give us some clues to the mineralogy, a study of the minerals themselves would be a more direct approach to identifying sediment sources. In particular, clay mineralogy and analysis of zircon crystals may reveal more about sediment entering the lake.

Conclusions

Recent sediments at Catahoula Lake are fine-textured and likely of Coastal Plain origins. Compared to deeper sediments, surface sediments are generally higher in titanium and zirconium; lower in calcium and potassium; and lower in pH. This chemistry occurs consistently across the lake bed on the surface, but below recent (~60 yr) sediments, 51% of sediment profiles are higher in pH and thus show influence of Mississippi River alluvial sediments. These basal Mississippi River alluvial sediments increase in pH toward neutral with depth. Mississippi River Alluvial Valley sediments are more prevalent in the northern and eastern parts of the lake while basal Coastal Plain sediments are more prevalent in the west and southwest. Coastal Plain sediments are likely entering the lake from the Little River and small streams along the bluffs to the west, which are all captive drainages into the lake, while Mississippi River Alluvial Valley sediments can enter through the diversion canal or French Fork of Little River as backwater flow. The recent shift to dominance of coastal plain sediments suggests hydrologic modification has disconnected the lake from sediment-bearing flows from the Mississippi River Alluvial Valley.

Carbon and nitrogen sequestration is within the range typical of wetlands, but at the extreme low end. Carbon and nitrogen relationships indicate that the carbon that is present is labile. Total nitrogen in the sediments of Catahoula Lake are low which is indicative of rapid denitrification and uptake of nitrogen by plants and accumulation into plant tissue and no excessive nitrogen loading.

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Chapter 5. Conclusions

Woody vegetation has been encroaching into the lake bed of Catahoula Lake and outcompeting herbaceous vegetation. Although encroachment has been occurring for at least 80 years, the rate of expansion is faster in recent decades than it was more than 50 years ago. There are three local patterns to expansion around the lake. Temporally continuous expansion, which suggests an ongoing process, is occurring near the major inflows and outflows of the lake. Long term stability of the tree front is more common in the north end of the lake, but management attempts may be masking the real patterns of expansion there. The rest of the lake is experiencing complex patterns of expansion that are possibly being affected by minor, localized disturbances.

Sedimentation at Catahoula Lake has been about 0.26 cm yr^{-1} for the past 60 years and may have decreased slightly after a peak sometime in the past about 200 years. Sedimentation is at a fairly uniform depth across the lakebed, suggesting redistribution after initial deposition.

Recent sediments at Catahoula Lake are fine-textured and likely of Coastal Plain origins. Compared to deeper sediments, surface sediments are generally higher in titanium and zirconium; lower in calcium and potassium; and lower in pH. This chemistry occurs consistently across the lake bed on the surface, but below recent (~60 yr) sediments, 51% of sediment profiles are higher in pH and thus show influence of Mississippi River alluvial sediments. These basal Mississippi River alluvial sediments increase in pH toward neutral with depth. Mississippi River Alluvial Valley sediments are more prevalent in the northern and eastern parts of the lake while basal Coastal Plain sediments are more prevalent in the west and southwest. Coastal Plain sediments are likely entering the lake from the Little River and small streams along the bluffs to the west, which are all captive drainages into the lake, while Mississippi River Alluvial Valley

sediments can enter through the diversion canal or French Fork of Little River as backwater flow. The recent shift to dominance of coastal plain sediments suggests hydrologic modification has disconnected the lake from sediment-bearing flows from the Mississippi River Alluvial Valley.

Carbon and nitrogen sequestration is low compared to other wetlands. C:N ratios indicate that the organic matter that is present is labile and related to recent primary production rather than sequestered, older organic matter. Total nitrogen in the sediments of Catahoula Lake is low, which may be indicative of rapid denitrification and uptake of nitrogen by or simply low nitrogen loading.

Compared to its condition prior to hydrologic alterations beginning in the 1920's, Catahoula Lake is about 15 cm shallower and the chemical composition of sediments is more acidic. Although these results are not sufficient to link these differences directly to ecological changes, it is likely the altered sedimentary and hydrologic environment is contributing to the increased dominance of woody vegetation.

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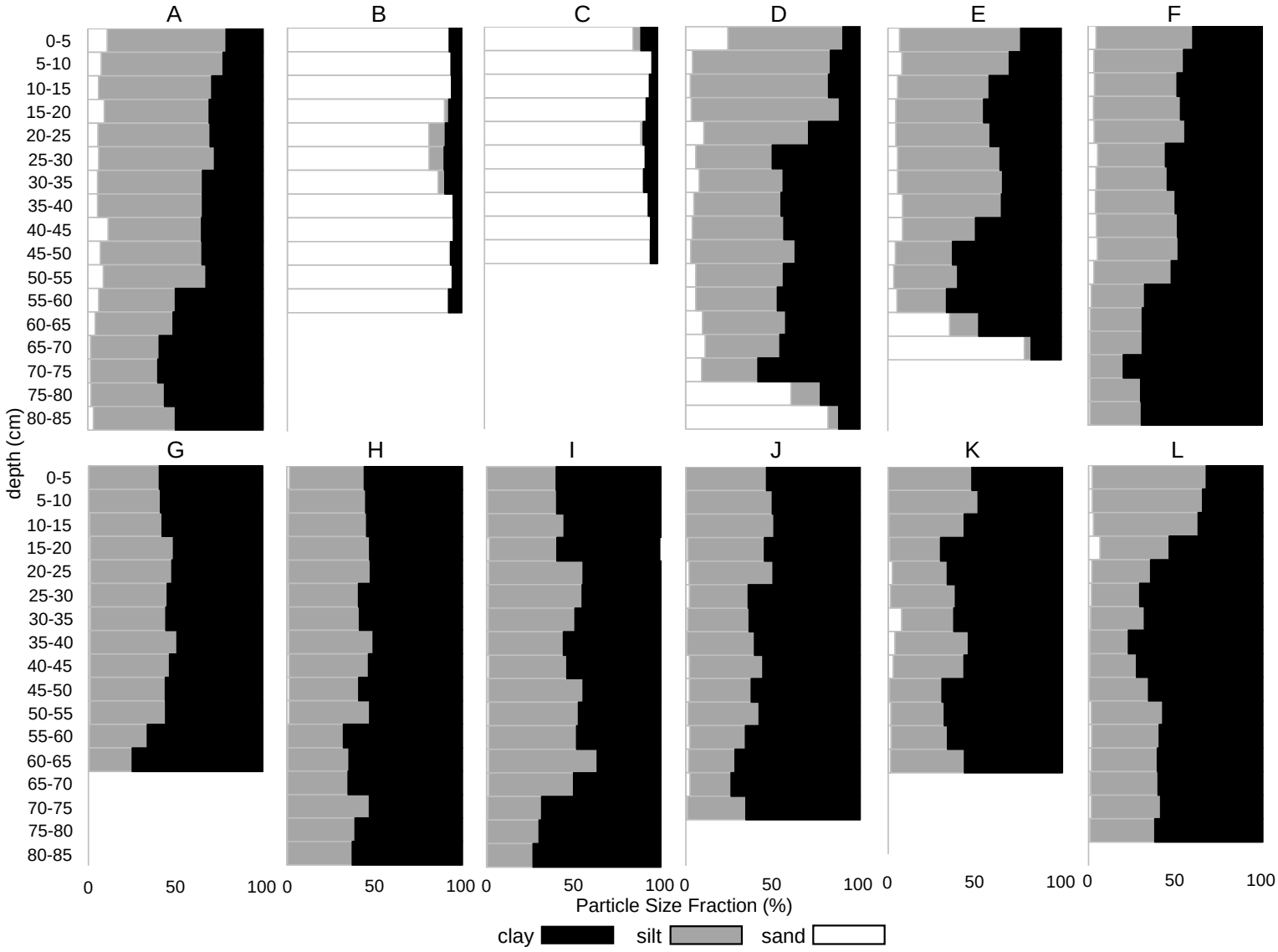
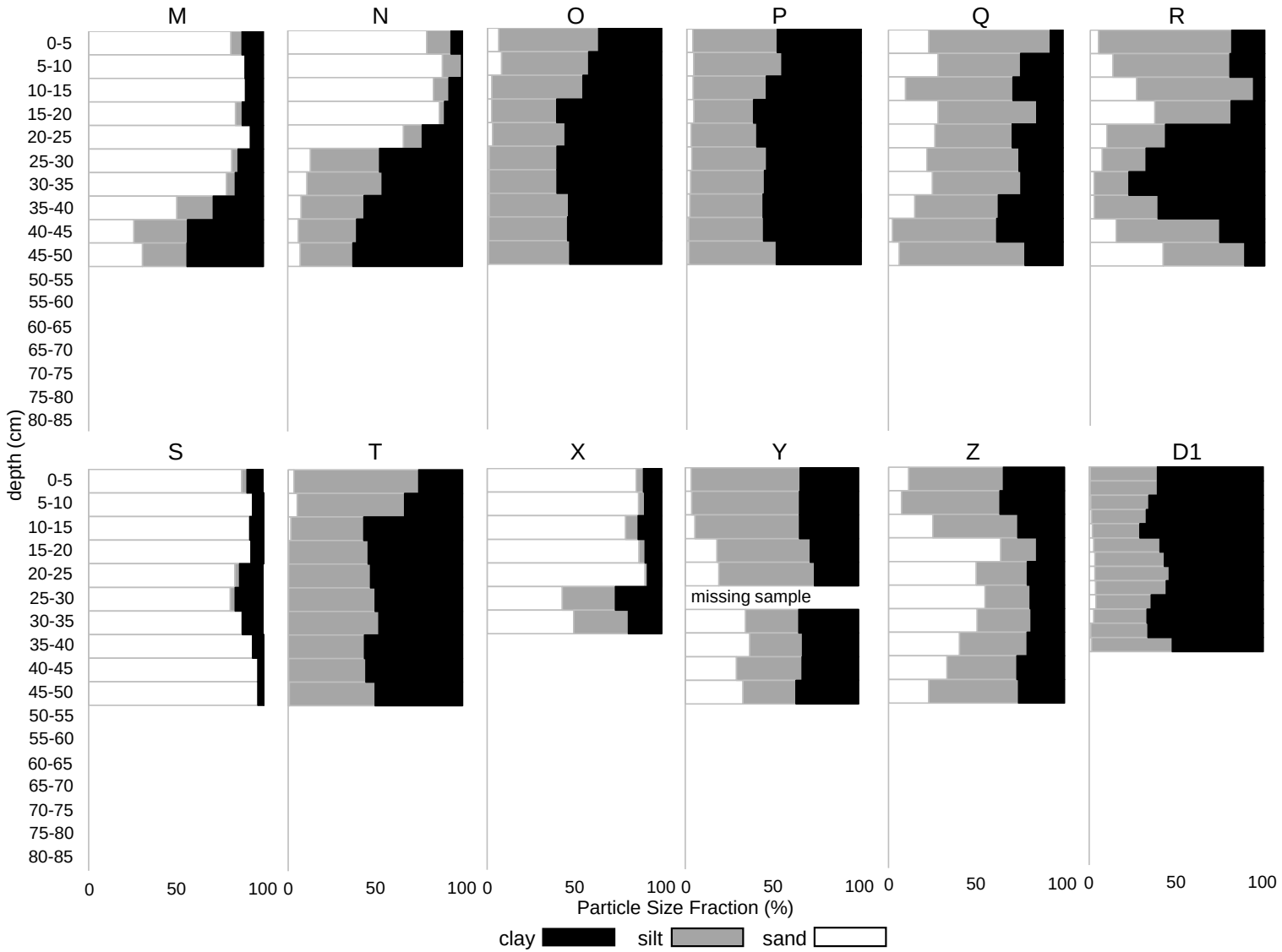
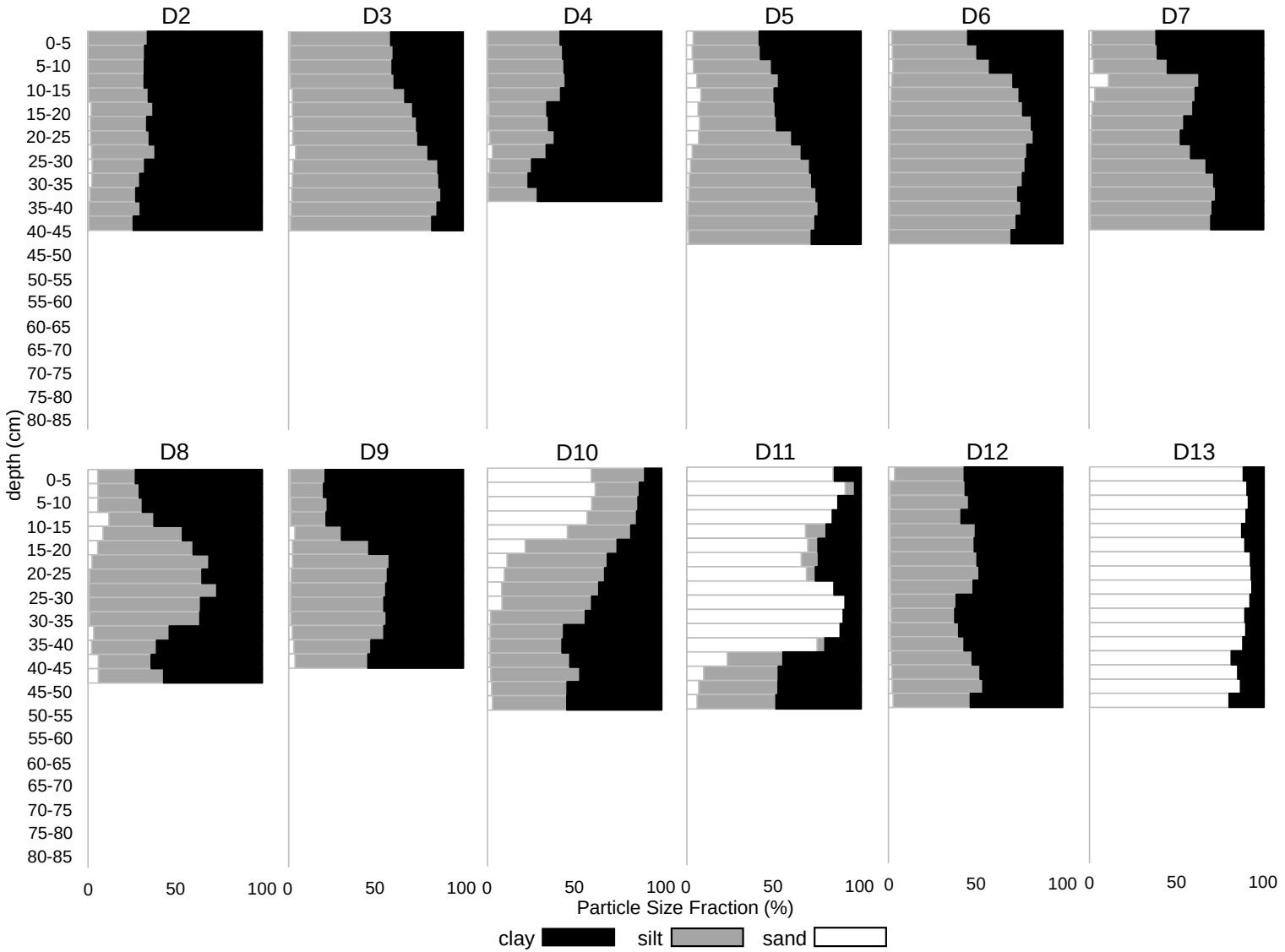
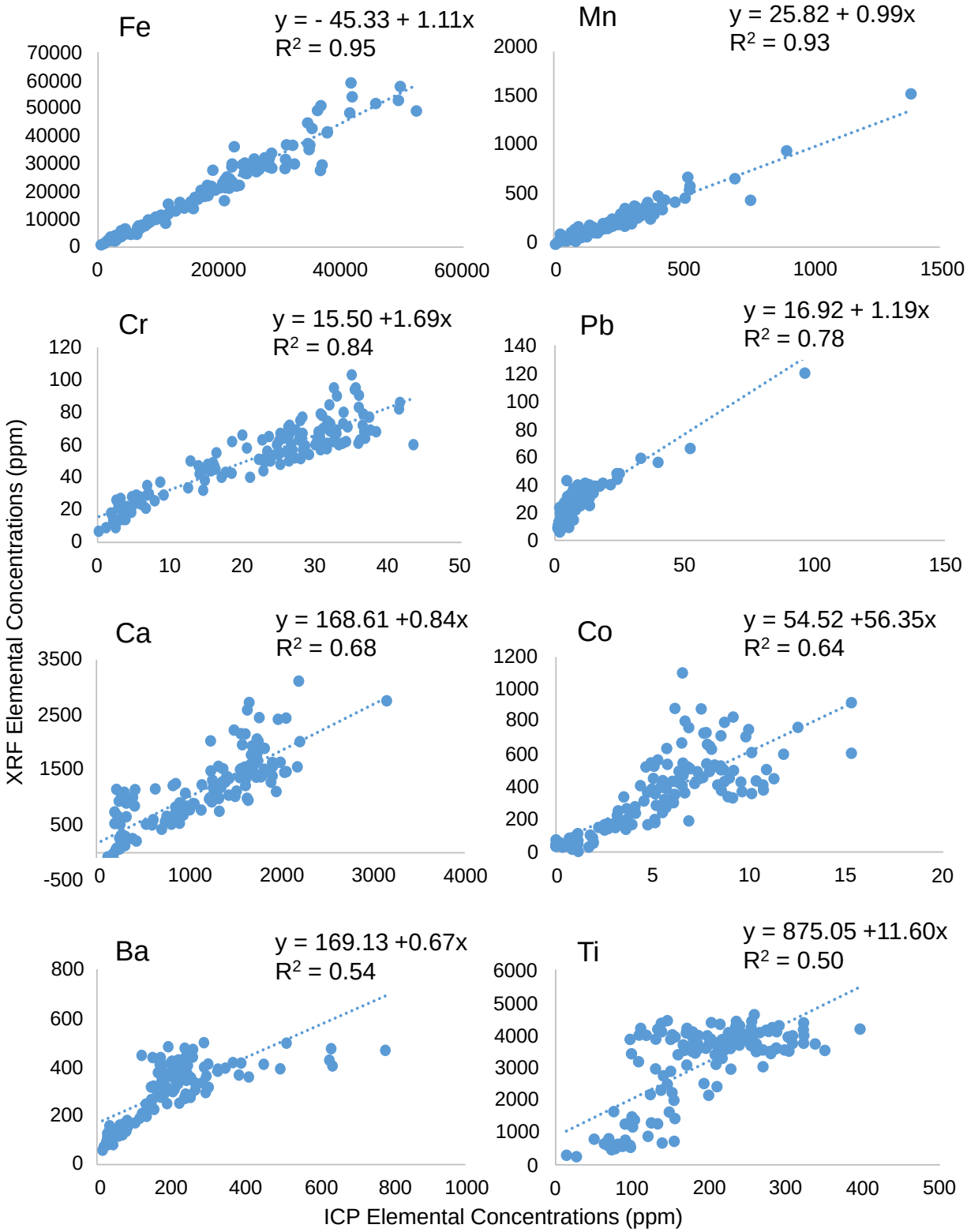
Appendix A. Particle size fractions with depth by profile

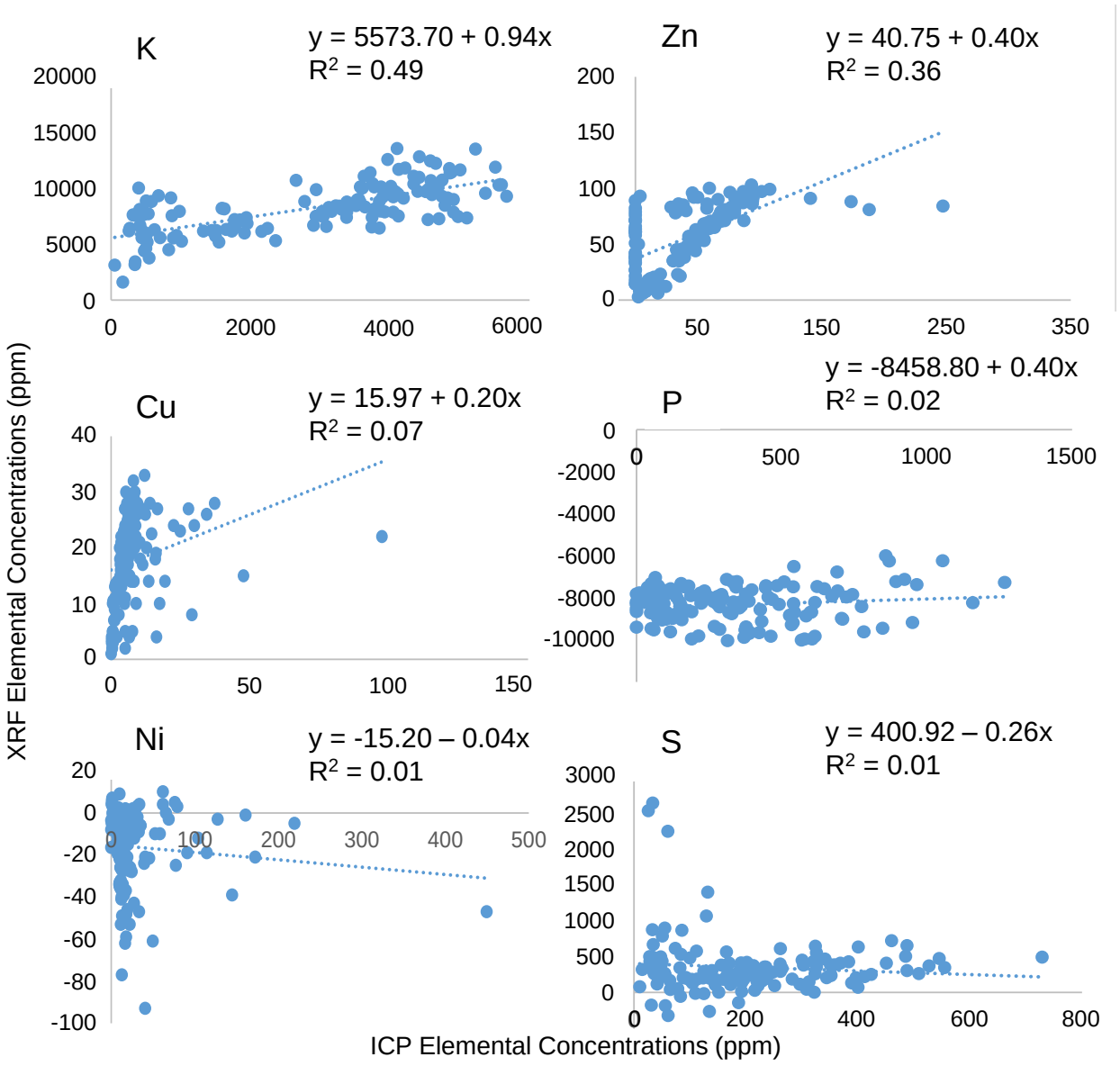



M
N
O
P
Q
R
S
T
X
Y
Z
D1
depth (cm)
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
missing sample
0
50
100
Particle Size Fraction (%)
clay
silt
sand


D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
depth (cm)
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
0
50
100
Particle Size Fraction (%)
clay
silt
sand

Appendix B. Linear regressions between PXRF and ICP elemental concentration data




K
y = 5573.70 + 0.94x
R2 = 0.49
Zn
y = 40.75 + 0.40x
R2 = 0.36
Cu
y = 15.97 + 0.20x
R2 = 0.07
P
y = -8458.80 + 0.40x
R2 = 0.02
Ni
y = -15.20 – 0.04x
R2 = 0.01
S
y = 400.92 – 0.26x
R2 = 0.01
XRF Elemental Concentrations (ppm)
ICP Elemental Concentrations (ppm)

Appendix C. Photographs of individual profiles

A. B. C. D. E. F. G. H.

I. J. K. L.

Giddings Probe sediment profiles, A-L.

D1.

D2.

D3.

D4.

D5.

D6.

D7.

D8.

Aluminum tube profiles D1- D8.

D9. D10. D11. D12. D13.

Aluminum tube profiles D9 - D13.

Vita

Karen Doerr Latuso, a native of Jacksonville, Florida, received her associate's degree at Florida State College at Jacksonville. Upon graduation, she transferred to the University of Florida in Gainesville, Florida and received a bachelor's degree in Journalism in 2001. Thereafter, she worked as a professional photographer and photography editor at The News-Star in Monroe, Louisiana; The Montgomery Advertiser in Montgomery, Alabama; and The Advocate in Baton Rouge, Louisiana.

In 2009, she decided to return to school to pursue a master's degree in the School of Renewable Natural Resources at Louisiana State University. She hopes to receive her master's degree with a minor in Agronomy in May 2014 and hopes to begin employment with a consulting firm or government agency as a wetlands or soil scientist.